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**PATENT- OG VAREMÆRKESTYRELSEN**

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Modtaget

## A LOW LOSS OPTICAL WAVEGUIDE, A METHOD OF ITS MANUFACTURE AND AN OPTICAL DEVICE

### 5 TECHNICAL FIELD

This invention relates to the manufacture of high quality optical films.

The invention relates specifically to an optical waveguide for guiding light in a predefined wavelength range, the optical waveguide comprising core and cladding regions for confining light, the core and/or cladding region or regions being formed on a substrate, and the whole or a part of the core and/or cladding region or regions comprising material of the stoichiometric composition  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v$ .

15 The invention furthermore relates to: A method of manufacturing an optical waveguide for guiding light in a predefined wavelength range, the optical waveguide comprising core and cladding regions for confining light, to an optical waveguide obtainable by the method and to an optical device comprising an optical waveguide.

20 This invention can be applied to all types of optical devices based on index guiding waveguide layers as well as photonic band gap related waveguide technologies. The invention may e.g. be useful in applications such as 25 optical communication systems, in particular for branching components (e.g. splitters) and components for wavelength division multiplexing (WDM) systems, e.g. telecommunication systems.

### 30 BACKGROUND ART

It is well known that it is difficult to fabricate optically transparent silica based waveguides with sufficiently low losses over a broad range of wavelengths. The commercially mature planar glass on silicon waveguide technology is 35 typically based on low-index contrast (less than 0.7%, the index difference between core and cladding being calculated as:

$$(\Delta n / \langle n \rangle) \cdot 100\% = 100\% \cdot 2 \cdot (n_1 - n_2) / (n_1 + n_2).$$

This more or less standard low-index technology platform ensures planar waveguide components with low propagation loss (< 0.05 dB/cm) and low fiber-to-chip coupling losses (e.g. < 0.3 dB/facet). The refractive index

- 5 difference between the waveguide core and cladding is generally achieved by doping the silica core material with higher refractive index oxides such as germanium, phosphorous oxide, titanium oxide, etc., in order to raise the refractive index above that of the cladding.
- 10 Increasing the index above 0.7% will allow for smaller bending radii without increasing the bending loss, and hence, smaller devices may be fabricated (cf. e.g. "A Low-Loss, compact wide-FSR-AWG using Planar Lightwave Circuit Technology", C. Doerr, FJ1 OFC 2003). This will allow for more devices per wafer, or alternatively create space for more complex
- 15 components with higher functionalities. Higher index contrast will eventually also open up for devices which cannot be made at a lower index contrast such as planar devices utilising a photonic band gap (PBG) effect. Recent developments in the design and fabrication of visible PBG waveguide devices in  $\text{Si}_3\text{N}_4$  type materials have been discussed extensively by M. D. B.
- 20 Charlton, et al., J. of Materials Science: Materials in Electronics 10 (1999) p. 429-440 (and references herein).

- As a promising production platform for higher index waveguides, an oxynitride ( $\text{SiO}_{x,\text{N}}_y$ ) type of material has been discussed extensively in the literature. It has been known for a long time, and shown by several groups, that a  $\text{SiO}_{x,\text{N}}_y$  type material can be fabricated with a tuneable refractive index which can be varied between that of  $\text{SiO}_2$  (1.455) and that of  $\text{Si}_3\text{N}_4$  (2.02) by conventional deposition techniques (such as chemical vapour deposition (CVD), plasma enhanced CVD (PECVD), atmospheric pressure CVD (APCVD) or low pressure CVD (LPCVD) processes, cf. e.g. "Reduction of hydrogen induced losses in PECVD- $\text{SiO}_{x,\text{N}}_y$  optical waveguides in the near infrared", H. Albers et al., in Proceedings of OFPW3.4, LEOS '95, IEEE Lasers and Electro-Optics Society 1995 Annual Meeting, 8th Annual Meeting. Although the high-end range of the refractive indices has been shown to have a high tendency for crack formation upon annealing to elevated temperatures, it has never the less been demonstrated that it is in

principle possible to tune the refractive index over the entire range, i.e. to achieve index differences from 0 % ( $\text{SiO}_2$ ) to 32.5% ( $\text{Si}_3\text{N}_4$ ).

- However, from the literature it is also known that  $\text{SiO}_x\text{N}_y$  films will contain
- 5 Si:N-H bonds giving rise to an absorption peak at a wavelength  $\lambda=1508$  nm due to an overtone of the Si:N-H vibration located around  $3300\text{ cm}^{-1}$  ( $k=1/(n\lambda)$ , where  $n$  is the order of the overtone, here  $n=2$ ). Even though the N-H vibration is at 1508 nm the "tail" of this peak extends into the telecom band giving rise to absorption at 1550 nm which is in the middle of the
- 10 telecom C-band (1530-1565 nm). Increasing the bandwidth to include the S- (1460-1530 nm) and the E- (1360-1460 nm) and the O-band (1260-1360 nm) the Si:N-H vibrations will be even more destroying when the aim is to fabricate low loss, high index contrast devices working over a broad wavelength range.
- 15 The intensity of the Si:N-H absorption peak can be lowered by annealing the as deposited  $\text{SiO}_x\text{N}_y$  film to elevated temperatures (cf. e.g. "Silicon Oxynitride Layers for Optical Waveguide Applications", R. Germann et al., J. of Electrochemical Society, 147(6), p. 2237-2241 (2000) or "Passband
- 20 flattened binary-tree structured add-drop multiplexers using SiON waveguide technology", Ph. D Thesis by Chris Roeloffzen, Twente, 2002 (ISBN 90-365-1803-2)). Annealing temperatures as high as 1150 °C have been reported in the literature giving losses at the peak maxima of around 0.6 dB/cm. Unfortunately, it is not possible to completely remove the absorption peak by
- 25 simple annealing, and furthermore, the annealing approach also has another drawback of increasing the stress in the film layer giving rise to a significant increase in the birefringence of the film (the degree of birefringence being defined by the difference between the refractive indices  $n_{TE}$  and  $n_{TM}$  of the transverse electric (TE) and transverse magnetic (TM) modes, respectively).
- 30 This is clearly an unwanted side effect of extensive annealing.

A decrease in hydrogen-bond related loss upon annealing of SiON-type material is also discussed in US patent applications US-2002-0182342, US-2002-0194876 and US-2002-0178760, among others.

- The variety of different CVD processes discussed in the literature can be grouped into two different categories, i.e. a type A process using NH<sub>3</sub> as one of the gasses from which the film layer is formed and a type B process where the films are nucleated from a gas composition which is not containing NH<sub>3</sub>.
- 5 We have mapped out various different PECVD combinations of type A and B processes. In accord with the findings in the literature, we find that there is a fairly high loss around 1508 nm due to the presence of Si:N-H bonds in films based on both types of processes (cf. FIG. 4). This is also the case after annealing up to 16 hours at 1150 °C. However, the loss due to vibrating N-H
- 10 bonds is slightly lower for films formed on the basis of a type B recipe as compared to films formed by a type A recipe. Intuitively this is also expected, since a film based on a type A recipe is expected to contain a higher density of N-H bonds since N-H bonds are directly introduced into the film layer through fragments of the NH<sub>3</sub> molecule, e.g. NH<sub>x</sub>, x=1, 2. In accord with the
- 15 literature we also saw that the absorption loss could be decreased by increasing the annealing temperature and/or the annealing time.

Unfortunately the improved losses obtained by annealing are still not low enough for low loss broad banded telecom related components.

20 One way to reduce the hydrogen concentration in silicon oxynitride material of the stoichiometric form Si<sub>a</sub>O<sub>x</sub>N<sub>y</sub>A<sub>z</sub>M<sub>v</sub>H<sub>u</sub> is according to WO-99/44937 to incorporate penta- or hexa-valent elements (A) from Group 15, 16 of the periodic system and/or mono- or di-valent metals (M) from groups 1, 2, 11 or 12 interstitially in the glass matrix. This is expected to reduce the hydrogen affinity of the nitrogen atoms and therefore to reduce the optical losses due to N-H-absorption. Preferred embodiments are elements of the stoichiometric form Si<sub>a</sub>O<sub>x</sub>N<sub>y</sub>A<sub>z</sub>M<sub>v</sub>H<sub>u</sub> wherein z≥y and/or v≥y, i.e. the concentration of Nitrogen is less than or equal to the concentration of A- (e.g. P, As, etc.) or M-elements (e.g. Li, Be, Cu, Zn. etc.).

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30

In EP-1295963 A2, EP-1273677 A2, and EP-1302792 A2 the optimization of process parameters such as flow rates, pressures, temperatures, gases, etc. in various steps of a PECVD process for deposition of silica films on a wafer 35 and subsequent heat treatment are described, the optimization being

performed with a view to reduce the optical absorption due to Si:N-H and Si:O-H oscillators.

- No characterisation of propagation loss measurements on a finished planar
- 5 waveguide has been performed in WO-99/44937. In EP-1295963 and EP-  
1273677 it is suggested to optimise the thermal treatment which allows the  
optical properties to be maintained while modifying the mechanical stress of  
the core. There is, however, no clear evidence for a correlation between  
10 optical loss and mechanical stress of the core layer, since the stress effect of  
the upper cladding layer is not considered in the spectroscopy  
characterisation of the core layer.

#### DISCLOSURE OF INVENTION

- 15 The object of the present invention is to provide an optical waveguide with  
low optical loss due to a reduced hydrogen bond-originated absorption. It is a  
further object to provide an optical waveguide with low optical loss due to  
absorption in a wavelength range used for optical transmission. In an  
embodiment of the invention, it is a further object to lower or remove  
20 absorption peaks due to hydrogen bonds in an optical waveguide. In an  
embodiment of the invention, it is a further object to lower or remove  
absorption peaks due to N-H bonds in an optical waveguide. In an  
embodiment of the invention, it is a further object to lower or remove  
25 absorption peaks due to O-H bonds in an optical waveguide. In an  
embodiment of the invention, it is a further object to lower or remove  
absorption peaks due to Si-H bonds in an optical waveguide.

- 30 The objects of the invention are achieved by the invention described in the  
accompanying claims and as described in the following.

- An optical waveguide for guiding light in a predefined wavelength range, the  
optical waveguide comprising core and cladding regions for confining light,  
the core and/or cladding region or regions being formed on a substrate, and  
35 the whole or a part of the core and/or cladding region or regions comprising  
material of the stoichiometric composition  $Si_aO_xN_yX_zH_v$ , is provided by the

invention wherein X is selected from the group of elements B, Al, P, S, Ge, As, Sb and combinations thereof, and the ratio y/z is larger than 1, such as larger than 1.2, such as larger than 1.5, such as larger than 1.8, such as larger than 2.0, such as larger than 2.5, such as larger than 3.0, such as  
5 larger than 3.5, such as larger than 4.0, such as larger than 4.5, such as larger than 5.0, such as larger than 5.5, such as larger than 6.0, such as larger than 7.0, such as larger than 8.0.

An advantage of the invention is that a low optical absorption in the  
10 waveguide may be achieved. In an embodiment of the invention, a low absorption in the waveguide may be obtained over a broad wavelength range, e.g. in the range 1530-1565 nm. Further, in an embodiment of the invention, a relatively low annealing temperature may additionally be used yielding a relatively low induced strain whereby a low birefringence may be  
15 achieved.

The present invention demonstrates that it is possible to make an optical waveguide with low optical absorption properties in the S-, C-, L- and O-bands. In particular, it is possible to lower the density of Si:N-H bonds to  
20 provide an absorption below 0.1 dB/cm (such as below 0.05 dB/cm) in a  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v$  type material where  $y > z$ , i.e. the concentration of X (e.g. P) is less than the concentration of N.

In an embodiment of the invention, it is further possible to tune the inherent  
25 stresses by adjusting the y/z ratio or by adding a third element or a combination of elements.

In the present context, the term "waveguide" is taken to mean any elongate guide structure which permits the propagation of a wave throughout its  
30 length despite diffractive effects, and possibly curvature of the guide structure. "An optical waveguide" based on total internal reflection is defined by an extended region of increased index of refraction relative to the surrounding medium. "An optical waveguide" based on a photonic band gap is defined by an extended core region surrounded by a photonic band gap  
35 material comprising a periodic pattern of holes or a periodic pattern of high index material. The strength of the guiding, or the confinement, of the wave

depends on the wavelength, the index difference and the guide width. Stronger confinement leads generally to narrower modes. An optical waveguide may support multiple optical modes or only a single mode, depending on the strength of the confinement. In general, an optical mode is

5 distinguished by its electromagnetic field geometry in two dimensions, by its polarization state, and by its wavelength. The polarization state of a wave guided in a birefringent material or an asymmetric waveguide is typically linearly polarized. However, the general polarization state may contain a component of nonparallel polarization as well as elliptical and unpolarized

10 components, particularly if the wave has a large bandwidth. If the index of refraction difference is small enough (e.g.  $\Delta n=n_1-n_2=0.036$ ) and the dimension of the guide is narrow enough (e.g. width  $W=3 \mu\text{m}$ ), the waveguide will only confine a single transverse mode (the lowest order mode) over a range of wavelengths. If the waveguide is implemented on the

15 surface of a substrate so that there is an asymmetry in the index of refraction above and below the waveguide, there is a cutoff value in index difference or waveguide width below which no mode is confined. A waveguide may be implemented in a substrate (e.g. by diffusion into the substrate), on a substrate (e.g. by applying a coating and etching away the surrounding

20 regions, or by applying a coating and etching away all but a strip to define the waveguide), inside a substrate (e.g. by contacting or bonding several processed substrate layers together). The optical mode which propagates in the waveguide has a transverse dimension which is related to all of the confinement parameters, not just the waveguide width.

25

The width and height of a waveguide element is in the present context taken in a transversal cross section of the waveguide core (i.e. in a cross section perpendicular to the intended direction of light guidance of said waveguide core elements at the location of a width measurement), the *width* being a

30 dimension of the core region of the waveguide element in question in a direction *parallel* to a reference plane defined by the opposing, substantially planar, surfaces of the substrate (x-direction in FIG. 6), the *height* being a dimension of the core region of the waveguide element in question in a direction *perpendicular* to the reference plane (in a direction of growth, y-direction in FIG. 6).

35

The term "the stoichiometric composition' of a material" reflects the relative number of units of the elements in question present in the material, e.g.  $\text{Si}_{0.97}\text{O}_{1.91}\text{N}_{0.09}\text{P}_{0.03}$  defining a material wherein (on average over a given volume of the material) for each 97 silicon atoms, 191 oxygen atoms, 9 nitrogen atoms and 3 phosphorus atoms are present. The suffixes or numbers a, x, y, z, v in the stoichiometric composition  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v$  represent the molar concentrations of the constituent elements calculated relative to the sum  $a+x+y+z+v$ , e.g. the relative concentration c(N) of the element nitrogen in the composition  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v$  equals  $y/(a+x+y+z+v)$ . In the present context, the atomic concentration of an element Q (e.g. H) measured in atomic% (at.%) is taken to mean  $c(Q) \cdot 100$  (i.e. for hydrogen  $c(H) \cdot 100 = v \cdot 100/(a+x+y+z+v)$  in a  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v$  material).

The volume – termed a 'given volume' above - over which the composition is averaged - is preferably the total volume of the sample or layer having a given intended stoichiometric composition, e.g. the volume of the core. Alternatively, the 'given volume' may be a representative part of the total volume, i.e. a macroscopic part of the sample, such as more than 1% of the total volume of the part or layer in question, i.e. statistically large enough to allow a meaningful average value. Alternatively, the 'given volume' may be a volume that is at least 5 times the volume expected to comprise one unit of the stoichiometric composition in question, such as at least 100 times, such as at least 1000 times. Alternatively, the 'given volume' may be defined by a dimension comparable to the wavelength  $\lambda$  of the propagating wave in question, such as 2 times  $\lambda$ , such as 10 times  $\lambda$ .

The atomic density (atoms/unit volume, e.g. atoms/cm<sup>3</sup>) of the different elements in a given sample may e.g. be determined by Secondary Ion Mass Spectrometry (SIMS) measurement or by an energy-dispersive X-ray analysis (EDX) measurement. The basic principles of both techniques are discussed extensively in various textbooks, see e.g. "Fundamentals of surface and thin films analysis", L. C. Feldman, J. W. Mayer, ISBN 0-444-00989-2, wherein - for example - quantitative analysis down to an accuracy of about 1 % by EDX is discussed. EDX is characterized by being a surface sensitive tool with electron penetration depths between 5 and 100 Å, depending on the energy of the incoming electron.

- A connection between atomic concentration and relative molar concentration may be estimated by assuming or measuring a certain mass density  $\rho(\text{SiONXH})$  of the resulting material (H may optionally be neglected due to its small contribution to the mass density). The atomic density  $N_{\text{at}}$  for a given element Q (Q = Si, O, N, X, H) is given by the formula

$$N_{\text{at}}(Q) = c(Q) \cdot \rho(\text{SiONXH}) \cdot N_a / M_{\text{tot}}$$

where  $c(Q)$ , as mentioned above, is the relative concentration of the element Q in the composition  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v$ ,  $N_a$  is Avogadro's number (the number of atoms or molecules in a mole) and  $M_{\text{tot}} = a \cdot M_{\text{Si}} + x \cdot M_{\text{O}} + y \cdot M_{\text{N}} + z \cdot M_{\text{X}} + v \cdot M_{\text{H}}$  is the mole mass (unit mass/mole, e.g. g/mole) of the  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v$ -material, where  $M_a$  is the atomic mass of element Q (e.g.  $M_{\text{Si}} = 28.086$  g/mole).

In an embodiment of the invention, the optical waveguide comprises a cladding region surrounding the core region. In an embodiment of the invention, the cladding and the core region comprises material of the stoichiometric composition  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v$  and wherein X is selected from the group of elements B, Al, P, S, Ge, As, Sb and combinations thereof, and the ratio  $y/z$  is larger than 1. The index difference between core and cladding may e.g. be provided by changing the  $y/x$  ratio (i.e. changing the [N]/[O]-concentrations, e.g. by changing the  $y/x$  ratio of the feed gas in a CVD-process). In an embodiment of the invention, the core and/or cladding region or regions are constituted essentially of material of the stoichiometric composition  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v$ . The term 'constituted essentially of material ...' is taken to refer to the elements of significance to the merits of the invention.

In an embodiment of the invention the, core region comprises material of the stoichiometric composition  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v$  and wherein X is selected from the group of elements B, Al, P, S, Ge, As, Sb and combinations thereof. In this embodiment, the cladding region or regions may comprise any type of material having an appropriate refractive index, e.g. a PBSG type glass or a PBG region.

In an embodiment of the invention the, waveguide comprises a core region and two or more surrounding cladding regions (e.g. two 'concentric' cladding regions wherein at least one of the cladding regions comprises material of

- the stoichiometric composition  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v$ , and wherein X is selected from the group of elements B, Al, P, S, Ge, As, Sb and combinations thereof. In this embodiment, the core region may comprise any type of material having an appropriate refractive index, e.g. a PBSG type glass or a PBG type glass
- 5      or a Ge doped silica glass. In this embodiment, a further cladding region or regions may comprise any type of material having an appropriate refractive index, e.g. a PBSG type glass or a PBG region or  $\text{SiO}_2$ .

In an embodiment of the invention, the ratio y/z is in the range 1.0 to 100,  
10    such as 1.0 to 20, such as 1.0 to 10, such as 1.5 to 8.0, such as 2.0 to 4.0,  
      such as 2.5 to 3.5.

In an embodiment of the invention, the ratio y/z is essentially equal to 3.  
15    In an embodiment of the invention, the ratio y/z is essentially equal to 7.

The term 'essentially equal to' is in the present context taken to mean being  
within 10% of the value in question, such as within 5%, such as within 1%.

20    In an embodiment of the invention, the number 'a' defining the relative  
      concentration of the element Si is in the range 0.1 to 3.5, such as in the  
      range 0.5 to 3.5 such as in the range 0.9 to 1.1 (e.g.  $\text{SiO}_2$ -like) or in the  
      range 2.9 to 3.1 (e.g.  $\text{Si}_3\text{N}_4$ -like).

25    In an embodiment of the invention, the number 'x' defining the relative  
      concentration of the element O is in the range 0 to 2.5, such as in the range  
      1.9 to 2.1 (e.g.  $\text{SiO}_2$ -like) or in the range 0 to 0.1 (e.g.  $\text{Si}_3\text{N}_4$ -like).

30    In an embodiment of the invention, the number 'y' defining the relative  
      concentration of the element N is in the range 0 to 4.5, such as in the range  
      3.9 to 4.1 (e.g.  $\text{Si}_3\text{N}_4$ -like) or in the range 0 to 0.5, such as in the range 0.02  
      to 0.3, such as in the range 0.03 to 0.2, such as in the range 0.04 to 0.10.

35    In an embodiment of the invention, the number 'z' defining the relative  
      concentration of the element X selected from the group comprising B, Al, P,  
      S, Ge, As, Sb and combinations thereof is in the range 0 to 0.3, such as in

the range 0 to 0.2, such as in the range 0.005 to 0.2, such as in the range 0.01 to 0.10.

In an embodiment of the invention, the number 'v' defining the relative  
5 concentration of the element H is defined by  $0 \leq v < 0.05$ .

In an embodiment of the invention, 'a' is in the range 0.8 to 1.2 and 'x' is in  
the range 1.8 to 2.2 and 'y' is in the range 0.01 to 0.5 and 'z' is in the range  
0.005 to 0.2. This illustrates the situation of a  $\text{SiO}_2$ -based SiONX-  
10 composition with comparatively small relative amounts of N and X-elements.

In an embodiment of the invention, 'a' is in the range 2.8 to 3.2 and 'x' is in  
the range 0.01 to 0.5 and 'y' is in the range 3.8 to 4.2 and 'z' is in the range  
0.005 to 0.2. This illustrates the situation of a  $\text{Si}_3\text{N}_4$ -based SiONX-  
15 composition with minor relative portions of O and X-elements.

In an embodiment of the invention, the number 'a' defining the relative  
concentration of the element Si is in the range 0.9 to 1.1, the number 'x'  
defining the relative concentration of the element O is in the range 1.9 to 2.1,  
20 the number 'y' defining the relative concentration of the element N is in the  
range 0.015 to 0.12, and the number 'z' defining the relative concentration of  
the element X is in the range 0.005 to 0.04.

In an embodiment of the invention, the waveguide core and/or cladding  
25 layers comprise material of the stoichiometric composition  $\text{Si}_{(1-z)}\text{O}_{(2-y)}\text{N}_y\text{X}_z$   
wherein X is an element from the group comprising B, Al, P, S, Ge, As, Sb or  
a combination thereof.

In an embodiment of the invention, the waveguide core and/or cladding  
30 layers consists essentially of material of the stoichiometric composition  
 $\text{Si}_{(1-z)}\text{O}_{(2-y)}\text{N}_y\text{X}_z$  wherein X is an element form the group comprising B, Al, P, S,  
Ge, As, Sb or a combination thereof.

In an embodiment of the invention, the waveguide core and/or cladding  
35 layers comprise material of the stoichiometric composition  $\text{Si}_{(1-z)}\text{O}_{(2-y)}\text{N}_y\text{P}_z$ . In  
an embodiment of the invention,  $0 < y \leq 0.2$  and  $0 < z \leq 0.1$ . In embodiments

of the invention, the atomic density of silicon  $N_{\text{at}}(\text{Si})$  in the range  $4.5 \cdot 10^{21} < N_{\text{at}}(\text{Si}) < 1.3 \cdot 10^{22}$ , such as in the range  $5.1 \cdot 10^{21} < N_{\text{at}}(\text{Si}) < 9.1 \cdot 10^{21}$ , the atomic density of oxygen  $N_{\text{at}}(\text{O})$  is in the range  $9.0 \cdot 10^{21} < N_{\text{at}}(\text{O}) < 2.7 \cdot 10^{22}$ , such as in the range  $1.0 \cdot 10^{22} < N_{\text{at}}(\text{O}) < 1.8 \cdot 10^{22}$ , the atomic density of nitrogen  $N_{\text{at}}(\text{N})$  is in the range  $0 < N_{\text{at}}(\text{N}) < 2.7 \cdot 10^{21}$ , such as in the range  $0 < N_{\text{at}}(\text{N}) < 1.8 \cdot 10^{21}$ , and the atomic density of phosphorus  $N_{\text{at}}(\text{P})$  is in the range  $0 < N_{\text{at}}(\text{P}) < 1.3 \cdot 10^{21}$ , such as in the range  $0 < N_{\text{at}}(\text{P}) < 9.0 \cdot 10^{20}$ .

10 In an embodiment of the invention, the atomic density of at least one of the elements Si, O, N, P in  $\text{Si}_{(1-z)}\text{O}_{(2-y)}\text{N}_y\text{P}_z$  is determined by SIMS.

In an embodiment of the invention, the atomic density of at least one of the elements Si, O, N, P in  $\text{Si}_{(1-z)}\text{O}_{(2-y)}\text{N}_y\text{P}_z$  is determined by EDX.

15 In an embodiment of the invention, X comprises more than one element, such as two or more, such as m in total, each having a relative concentration compared to the total concentration z of X termed  $z_1$  for X(1) and  $z_2$  for X(2), etc., and  $z_m$  for X(m). The term "the element or elements X of the material

20  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v$  comprises at least  $q_1\%$  of the element X(1)" is in the present context taken to mean that  $q_1/100 = z_1/z$ , where  $z=\text{SUM}(z_i)$ ,  $i=1, 2, \dots, m$ , where SUM( $z_i$ ) denotes the algebraic sum of the elements  $z_i$ . The relative concentration of the element X(i) in the material  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v$ , on the other hand, is  $z_i/(a+x+y+z+v)$ .

25 In an embodiment of the invention, the element or elements X or the material  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v$  comprises at least 50% phosphorus such as at least 75% phosphorus such as at least 90% phosphorus, such as 100% phosphorus.

30 In an embodiment of the invention, the element or elements X or the material  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v$  comprises at least two elements X(1), X(2), ..., X(n) where  $n \leq 7$ , selected from the group comprising B, Al, P, S, Ge, As, Sb of relative concentrations  $z_1, z_2, \dots, z_n$ , respectively, where  $z=z_1+z_2+z_3+\dots+z_n$  and wherein  $z_1/z$  is larger than 0.50 such as larger than 0.75 such as larger than 0.90.

In general, the addition of P, Ge and N to silica glass base increases the refractive index, whereas the addition of B decreases the refractive index of the resulting waveguide material. In general, the addition of B and P increases the flow properties of a resulting silica glass. Interestingly, we have 5 in connection with the present invention observed that the addition of P to SiON lowers the refractive index, suggesting that P might substitute N.

Recently it has been suggested (US2003/0021578) that the addition of Ge to 10 a BPSG material allows for a decrease in P while retaining the same refractive index. As a consequence of the lower P-concentration, a smaller density of  $\text{BPO}_4$  is formed during subsequent annealing, allowing for an improved reflow mechanism enabling the fabrication of high-aspect ratio structures without keyhole formation (i.e. without voids or inclusions in the cladding material). Similarly, an improved reflow mechanism enabling the 15 fabrication of high-aspect ratio structures without keyhole formation might be expected for  $\text{Si}_x\text{O}_y\text{N}_z\text{H}$ , with X(1) = P, X(2) = Ge and X(3) = B.

In an embodiment of the invention, n=2 and X(1) is P and X(2) is B. In an embodiment of the invention, n=2 and X(1) is P and X(2) is Ge. This has the 20 advantage that the relative concentrations of P and B or Ge may be used to fine tune the resulting refractive index.

In an embodiment of the invention, n=3 and X(1) is P, X(2) is B and X(3) is Ge. This has the advantage that the relative concentrations of P, B and Ge 25 may be used to fine tune the resulting refractive index.

In an embodiment of the invention, the optical absorption peak at  $\lambda=1508$  nm due to Si:N-H bonds is smaller than 0.1 dB/cm, such as smaller than 0.05 dB/cm, such as smaller than 0.01 dB/cm, as measured e.g. by a planar 30 version of a conventional cut-back-method.

The concentration of H is preferably so small that the optical absorption peak due to Si:N-H bonds is smaller than 0.1 dB/cm at  $\lambda=1508$  nm, such as 35 smaller than 0.05 dB/cm, such as smaller than 0.01 dB/cm. In an embodiment of the invention, the concentration of H is smaller than 10000 ppm (i.e.  $v/(a+x+y+z+v) < 10^{-2}$ ), such as smaller than 1000 ppm, such as

- smaller than 100 ppm, such as smaller than 10 ppm. In an embodiment of the invention, the relative concentration of H is much smaller than the relative concentration of N, i.e. e.g.  $v < 10^{-2}y$ , such as  $v < 10^{-3}y$ , such as  $v < 10^{-4}y$ . In an embodiment of the invention, the relative concentration of H is
- 5 much smaller than the relative concentration of X, i.e. e.g.  $v < 10^{-2}z$ , such as  $v < 10^{-3}z$ , such as  $v < 10^{-4}z$ , where X is an element selected from the group comprising B, Al, P, S, Ge, As, Sb and combinations thereof. In an embodiment of the invention, the atomic concentration of hydrogen is less than 25 at.%, such as less than 15 at.%, such as less than 5 at.%.
- 10 In an embodiment of the invention, the concentration of H is larger than the concentration of N or X or the concentration of N plus X (i.e.  $v > y$ , or  $v > z$  or  $v > y+z$ ). However, in this case a part of the hydrogen atoms may not contribute to the optical absorption around 1508 nm and/or may not be
- 15 bound in the material in an N-H type bond. In an embodiment of the invention, the concentration of hydrogen atoms in the material  $Si_aO_xN_yX_zH_v$  is in the range 5 to 25 at.%, such as in the range 10 at.% to 20 at.%.
- The hydrogen concentration of a sample may e.g. be determined by
- 20 hydrogen nuclear reaction analysis (cf. e.g. "Fundamentals of surface and thin films analysis", L. C. Feldman, J. W. Mayer, ISBN 0-444-00989-2).
- It should be noted that a small percentage of nitrogen impurity will mostly be
- 25 present in CVD deposited glass when nitrogen is used as carrier gas or for example as part of the oxygen containing reaction gasses (i.e.  $N_2O$  or  $NH_3$ ). The percentages of the nitrogen impurity in such deposited glasses may be low and are often not measured or reported, partly because of the difficulty of ascertaining the nitrogen content with a reasonable accuracy. The analytical detection problem represents one reason why the unusual properties and
- 30 advantages of chemically bound nitrogen in glasses are neither fully understood nor appreciated in the industry.

In an embodiment of the invention, the core and/or cladding region comprises material having a refractive index in the range 1.45 – 2.02, such as in the range 1.45 to 1.60, such as in the range 1.48 to 1.56 at a wavelength of 1550 nm. This may e.g. be achieved by addition of minor

amounts of dopant ions such as Ge or Al. This has the advantage of allowing the manufacture of a relatively high index-waveguide while avoiding the N-H-absorption peak.

- 5 The term "the refractive index" of a region or volume represented by a particular cross sectional area of the waveguide is in the present context taken to mean the geometrical refractive index. If the region in question is constituted by one homogeneous material with a specific refractive index, the geometric refractive index is the normal refractive index for a homogeneous  
10 material. If the region in question is constituted by several smaller areas each of a homogeneous material, the geometric refractive index is the geometrically weighted average of the normal refractive indices of these smaller areas, i.e. the sum of the products of refractive index  $n_i$  and ratio  $A_i/A$  of the partial area  $A_i$  in question to the area  $A$  of the whole region being  
15 considered (i.e.  $\text{SUM}(n_i \cdot (A_i/A))$ ,  $i=1, 2, \dots, m$ , where  $m$  is the number of smaller (or partial) areas constituting the region being considered).

In some cases the effective refractive index  $n_{\text{eff}}$  is conveniently used to characterize properties of an optical waveguide. Instead of considering the  
20 true waveguide structure with core and cladding the light propagation may be described as a plane wave propagating in a homogeneous medium having a refractive index  $n_{\text{eff}}$ , the so-called effective refractive index. This effective index is rooted in eigenvalue equations originating from Maxwell's equations. The effective refractive index of a bound mode is greater than the cladding  
25 refractive index, and lower than the core refractive index. The effective index is furthermore a function of the waveguide core cross-sectional geometry, see e.g. H. Nishihara et al., "Optical Integrated Circuits", McGraw-Hill (1989).

An optical waveguide according to the invention may be used for guiding  
30 light of any wavelength. In an embodiment of the invention, the optical waveguide is adapted to guide light in a wavelength range located in the range of 250 nm to 3.6  $\mu\text{m}$ , such as in the range of 850 nm to 1800 nm. In an embodiment of the invention, the optical waveguide is adapted to guide light comprising wavelengths in the range of 1260 nm to 1660 nm, such as in  
35 the range 1530-1565 nm, or in the range 1460-1530 nm, or in the range 1360-1460 nm, or in the range 1260-1360 nm.

In an embodiment of the invention, the waveguide core and/or cladding further comprises one or more of the rare earth (RE) elements (i.e. the elements Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu). In an

- 5 embodiment of the invention, one or more of the RE elements are present in concentrations in the range 50 to 5000 ppm (mole/mole) i.e. in a material of the stoichiometric composition  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v(\text{RE})_q$ ,  $50 \cdot 10^{-6} < q/(a+x+y+z+v+q) < 5000 \cdot 10^{-6}$ . This has the advantage of enabling the formation of an active waveguide (for an amplifier or laser type functionality) in combination with the
- 10 low absorption loss features.

In an embodiment of the invention, the core and/or cladding region or regions additionally comprise Ge in sufficient amounts to minimise internal stress due to thermal expansion or contraction of the waveguide. This has

- 15 the advantage of enabling a reduce birefringence of the core and/or cladding layers In an embodiment of the invention, the material(s) of the core and/or cladding region or regions comprise less than 5 at.% Ge.

- In an embodiment of the invention, the thermal expansion of one or more of  
20 the layers constituting the core and cladding regions of the waveguide is/are adapted to the thermal expansion of the substrate by adding one or more TE-dopant elements to said one or more layers of the waveguide. 'TE-dopant' is used as an abbreviation for 'Thermal Expansion influencing dopants'.

- 25 In an embodiment of the invention, the TE-dopant element or elements is/are selected from the group of elements comprising Al, B, F, Ge, P, Ti, or combinations thereof.

- 30 In an embodiment of the invention, the TE-dopant element or elements are present in the core/and or cladding region or regions in molar concentrations in the range 0 to 5%, i.e. taken relative to the sum of the molar concentrations of Si, O, N, X, H, (and possibly RE-dopants) and TE-dopants.

- 35 In an embodiment of the invention, the TE-dopant element or elements are present in the core/and or cladding region or regions in amounts sufficient to

provide a coefficient of thermal expansion between  $1 \cdot 10^{-7}$  °C<sup>-1</sup> and  $15 \cdot 10^{-7}$  °C<sup>-1</sup>.

In an embodiment of the invention, the optical waveguide takes the form of a  
5 planar waveguide formed on a substrate. In an embodiment of the invention,  
the substrate is silicon. This has the advantage of facilitating large scale  
production. In an embodiment of the invention, the substrate is quartz. This  
has the advantage of inherently a lower cladding layer, and furthermore,  
induced stress from the substrate (e.g. silicon) is avoided.

10 In an embodiment of the invention, the waveguide is part of a photonic  
crystal structure, allowing the propagation of electromagnetic energy in a  
certain wavelength range to be controlled by the introduction of periodic  
structural features providing a photonic band gap (PBG).

15 In an embodiment of the invention, the optical waveguide is manufactured by  
chemical vapour deposition (CVD), such as plasma enhanced CVD (PECVD)  
or Atmospheric Pressure CVD (APCVD). This has the advantage of  
providing an industrially proven manufacturing technology which is reliable  
20 and readily scalable for large volumes.

Alternatively the waveguides may be manufactured by other techniques such  
as flame hydrolysis deposition or techniques for spinning materials on glass.

25 A method of manufacturing an optical waveguide for guiding light in a  
predefined wavelength range, the optical waveguide comprising core and  
cladding regions for confining light is furthermore provided by the present  
invention, the method comprising the steps of  
A) providing a substrate,  
30 B) forming a lower cladding layer on the substrate,  
C) forming a core region of said optical waveguide on the lower cladding  
layer,  
D) forming an upper cladding layer to cover the core region and the lower  
cladding layer;  
35 wherein the whole or a part of said waveguide core and/or cladding region or  
regions comprise material of the stoichiometric composition Si<sub>a</sub>O<sub>x</sub>N<sub>y</sub>X<sub>z</sub>H<sub>v</sub> and

X is selected from the group of elements B, Al, P, S, Ge, As, Sb and combinations thereof, and wherein  $y > z$ , such as larger than 1.2, such as larger than 1.5, such as larger than 1.8, such as larger than 2.0, such as larger than 2.5, such as larger than 3.0, such as larger than 3.5, such as

- 5 larger than 4.0, such as larger than 4.5, such as larger than 5.0, such as larger than 5.5, such as larger than 6.0, such as larger than 7.0, such as larger than 8.0.

The method is easily integrated into proven state of the art manufacturing  
10 technologies of optical waveguides and integrated optical components having the advantages of corresponding (above mentioned) optical waveguides is provided.

In an embodiment of the invention,  $0.5 < a < 3.5$ ,  $0 < x < 2.5$ ,  $0 < y < 4.5$ ,  $0 <$   
15  $z < 0.2$ .

In an embodiment of the invention,  $0.5 < a < 3.5$ ,  $0 < x < 2.5$ ,  $0 < y < 4.5$ ,  $0 <$   
 $z < 0.2$  and  $0 \leq v < 0.05$ .

20 In an embodiment of the invention,  $v \geq 0.05$ . In an embodiment of the invention,  $v$  is larger than  $y$  or  $z$  or  $y+z$ . In an embodiment of the invention, the atomic concentration of hydrogen in the material  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v$  is less than 25 at.%, such as less than 15 at.%, such as less than 5 at.% or in the range 5 to 25 at.%, such as in the range 10 at.% to 20 at.%.

25 In an embodiment of the invention,  $0.5 < a < 3.5$ ,  $0 < x < 2.5$ ,  $0 < y < 4.5$ ,  $0 <$   
 $z < 0.2$ .

In an embodiment of the invention,  $0.8 < a < 1.2$ ,  $1.8 < x < 2.2$ ,  $0.01 < y <$   
30  $0.5$ ,  $0.005 < z < 0.2$ .

In an embodiment of the invention,  $0.9 < a < 1.1$ ,  $1.9 < x < 2.1$ ,  $0.015 < y <$   
 $0.12$ ,  $0.005 < z < 0.04$ .

35 In an embodiment of the invention,  $2.8 < a < 3.2$ ,  $0.01 < x < 0.5$ ,  $3.8 < y <$   
 $4.2$ ,  $0.005 < z < 0.2$ .

- In an embodiment of the invention, step C) comprises the sub-steps  
C1) forming a core layer on the lower cladding layer,  
C2) providing a core mask comprising a core region pattern corresponding to  
5 the layout of the core region of said optical waveguide, and  
C3) forming core regions using the core mask, a photolithographic and an  
etching process. This has the advantage of availing the use of industry  
standard manufacturing processes, well-known from the manufacture of  
integrated semiconductor as well as optical circuits.
- 10 In an embodiment of the invention, the substrate is a silicon or quartz  
substrate.
- In an embodiment of the invention, the optical waveguide is manufactured by  
15 chemical vapour deposition (CVD), such as plasma enhanced CVD (PECVD)  
or Atmospheric Pressure CVD (APCVD). This has the advantage of  
providing an industrially proven manufacturing technology which is reliable  
and readily scalable for large volumes.
- 20 In an embodiment of the invention, a standard cluster tool CVD process  
chamber type PECVD-apparatus from Surface Technology Systems is used  
for the formation of layers on the substrate.
- In an embodiment of the invention,  
25 the N<sub>2</sub> flow rate: is in the range 0-2000 sccm,  
the N<sub>2</sub>O flow rate is in the range 100-400 sccm,  
the NH<sub>3</sub> flow rate is in the range 0-300 sccm,  
the SiH<sub>4</sub> flow rate is in the range 0-30 sccm,  
the 5% PH<sub>3</sub> in N<sub>2</sub> flow rate is in the range 0-50 sccm,  
30 the power is in the range between 0 and 1200 W,  
the pressure is in the range 50-500 mTorr,  
the temperature is in the range 200-400 °C,  
the frequency is around 380 kHz or around 13.56 MHz,

The unit sccm is short for Standard Cubic Centimeters per Minute being defined as a cubic centimetre at standard pressure and temperature (i.e. atmospheric pressure and 0 °C).

- 5 An optical waveguide obtainable by a method of manufacturing as described above is moreover provided by the present invention. Such a waveguide has the same advantages as for the waveguides outlined above.

- 10 An optical device comprising an optical waveguide as defined above is further provided by the present invention. Examples of devices wherein waveguides according to the invention could be useful are e.g. splitters, couplers, e.g. an arrayed waveguide grating (AWG), a generalized Mach-Zehnder interferometer, and any other functional units being part of an optical communication system.

- 15 It should be emphasized that the term "comprises/comprising" when used in this specification is taken to specify the presence of stated features, integers, steps or components but does not preclude the presence or addition of one or more other stated features, integers, steps, components or groups thereof.

#### BRIEF DESCRIPTION OF DRAWINGS

- 25 The invention will be explained more fully below in connection with a preferred embodiment and with reference to the drawings in which:

- 30 FIG. 1 shows the refractive index at  $\lambda=1550$  nm for the core region of various optical waveguides according to the invention, before and after annealing, respectively,

- 35 FIG. 2 shows corresponding values of layer thickness and refractive index at  $\lambda=1550$  nm for the core region of a waveguide according to the invention as a function of annealing temperature,

FIG. 3 shows a measure for the birefringence at  $\lambda=1550$  nm of a waveguide according to the invention as a function of annealing temperature,

5 FIG. 4 shows optical absorption loss in dB/cm from  $\lambda=1500$  nm to  $\lambda=1600$  nm for a waveguide manufactured according to different processing conditions, respectively, 'with NH<sub>3</sub>', 'without NH<sub>3</sub>' and a 'new process' according to the invention,

10 FIG. 5 shows optical propagation loss in dB at  $\lambda=1550$  nm for a waveguide according to the invention as a function of waveguide length (in cm) and mode (TE or TM), and

15 FIG. 6 shows a cross section of a part of an optical component according to the invention.

15

The figures are schematic and simplified for clarity, and they just show details which are essential to the understanding of the invention, while other details are left out. Throughout, the same reference numerals are used for 20 identical or corresponding parts.

#### MODE(S) FOR CARRYING OUT THE INVENTION

25 A process according to the invention may be optimized as regards providing a waveguide with a low optical absorption around  $\lambda=1508$  nm using one or more of the hints listed below:

1. Avoid NH<sub>3</sub> since this is an additional hydrogen source and contains an 30 NH-bond.
2. Lower the SiH<sub>4</sub> flow since this is also a potential hydrogen source.
3. Increase the plasma power since more Si-H bonds will be broken allowing for less incorporation of hydrogen containing Si fragments as compared to when the plasma process is driven at a lower power where 35 it is expected that a smaller amount of Si-H bonds are broken.

4. Increase the total flow since this will flush out the reaction products the most undesirable being hydrogen and hydrogen containing fragments.
5. Increase the temperature since this is expected to decrease the concentration of hydrogen in the plasma grown PECVD glass.
- 5 6. Changing the pressure will change the fragmentation degree of the molecules in the plasma and hereby changing the properties of the grown film.
7. Changing the frequency of the energy source driving the plasma will alter the properties of the PECVD grown film.
- 10 8. Add a small amount of (optionally diluted) PH<sub>3</sub>.

A Combination of one or more of the above mentioned elements may result in a total removal of the N-H peak an overtone of which causes extensive absorption at 1508 nm when a PECVD grown core glass is used as an  
15 optical waveguide.

In various embodiments of the present invention, the waveguide materials comprise a number of the following elements Si, O, N, X ('X' = B, Al, P, S, Ge, As, Sb), H, RE-dopants ('RE' = Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu ), TE-dopants ('TE' = Al, F, Ge, Ti, B, P) in the stoichiometric composition Si<sub>a</sub>O<sub>x</sub>N<sub>y</sub>X<sub>z</sub>H<sub>v</sub>(RE)<sub>q</sub>(TE)<sub>p</sub>, where X denotes one or more of the elements 'X' for controlling refractive index and/or optical absorption properties and/or thermal expansion properties, RE one or more of the rare-earth elements 'RE' for controlling optical gain, and TE one or more of the elements 'TE' for controlling thermal expansion.  
20  
25

PECVD also known as Plasma CVD (PCVD) and Low Pressure Chemical Vapour Deposition (LPCVD) are described in further detail in Hiroshi Nishihara, Masamitsu Haruna and Toshiaki Suhara "Optical integrated circuits", McGraw-Hill Book Company, (1989), and in Chapter 3 in Marc Madou: "Fundamentals of Microfabrication", ISBN 0-8493-9451-1, which are incorporated herein by reference.  
30

**EXAMPLE 1**  
35 A PECVD core glass has been grown on a standard PECVD apparatus (in this case a standard cluster tool CVD process chamber type PECVD-

apparatus from STS (Surface Technology Systems plc of Newport, South Wales, UK) is used for the formation of layers on a silicon substrate using the following parameters:

- 5    a) SiH<sub>4</sub> flow rate: 20 sccm
- b) N<sub>2</sub>O flow rate: 100-400 sccm
- c) N<sub>2</sub> flow rate: 2000 sccm
- d) 5% PH<sub>3</sub> in N<sub>2</sub> flow rate: 10 sccm
- e) Power: 700 W
- 10   f) Pressure: 250 mTorr
- g) Temperature: 350 °C
- h) Frequency: 380 kHz

FIG. 1 shows the refractive index at  $\lambda=1550$  nm for the core region of various optical waveguides according to the invention, before and after annealing, respectively. Annealing was performed at 1100 °C for 4 hours in a nitrogen atmosphere.

The refractive index may easily be tuned in a fairly large range and significantly larger than indicated in FIG. 1. The refractive index change is completely governed by the ratio of nitrogen to oxygen atoms in the PECVD feed gas (at constant SiH<sub>4</sub> flow) as indicated by the linear relation of the refractive index as a function of the [N]/[O] ratio (cf. FIG. 1). Here [N] = 2•[N<sub>2</sub>O] + 2•[N<sub>2</sub>] + 0.95•[5%PH<sub>3</sub>/N<sub>2</sub>] and [O] = [N<sub>2</sub>O] where [xx] denotes the flow rate of species xx in sccm.

FIG. 2 shows corresponding values of layer thickness and refractive index at  $\lambda=1550$  nm for the core region of a waveguide according to the invention as a function of annealing temperature. Open symbols indicate refractive index at  $\lambda=1550$  nm. Closed symbols indicate layer thickness in  $\mu\text{m}$ . Atomic densities of nitrogen and phosphorus are [N] =  $1.30 \cdot 10^{21}$  atoms/cm<sup>3</sup> and [P] =  $4.58 \cdot 10^{20}$  atoms/cm<sup>3</sup>, respectively, as determined by calibrated SIMS.

The index of the as deposited PECVD glass can be modified upon annealing as seen in FIG. 2. The index change is initiated above approximately 800 °C and continues beyond 1100 °C.

FIG. 3 shows a measure for the birefringence at  $\lambda=1550$  nm of a waveguide according to the invention as a function of annealing temperature.

- 5 The index change is correlated with an increase in the birefringence as seen from FIG. 3 where the difference between refractive index for TE and TM modes measured at  $\lambda=1550$  nm is plotted as a function of the temperature. Thus, it is suggested to use a relatively low annealing temperature in order to minimize the build up of birefringence. However, the applied annealing  
10 temperature should of cause be compatible with subsequent cladding procedure.

- An optical component including a waveguide according to the present invention may be manufactured by a method comprising the steps of  
15 A) providing a substrate,  
B) forming a lower cladding layer on the substrate,  
C1) forming a core layer on the lower cladding layer,  
C2) providing a core mask comprising a core region pattern corresponding to the layout of the core regions of optical waveguide elements of the  
20 component,  
C3) forming core regions using the core mask, a photolithographic and an etching process,  
D) forming an upper cladding layer to cover the core region pattern and the lower cladding layer, and  
25 E) annealing in a controlled atmosphere.

- The annealing step E) may e.g. be performed after the deposition of the core layer and/or in connection with successive upper deposition and annealing steps.  
30 In an embodiment of the present invention a clean and bare Silicon wafer (used as substrate, step A) is firstly oxidized (step B) to provide an optical isolation layer (the 'buffer layer') of silica sufficiently thick that the magnitude of the evanescent field tail of the field pertaining to the waveguide cores is  
35 sufficiently low to ensure negligible propagation loss. On top of the buffer layer a layer (termed the 'core layer') of  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v(\text{RE})_q(\text{TE})_p$  (with meaning

as described above) is deposited (step C1), containing one or more dopants that effectively act to control the refractive index of the layer, to make it optically active, and/or to adapt its thermal expansion properties to those of the substrate. Depending upon the method used to deposit the core layer a

5 high temperature treatment (known as an anneal step) may be advantageous in order to stabilize the optical and/or mechanical properties of the layer. The optical waveguide circuitry is defined through standard optical lithography where a UV-transparent plate containing typically a chromium pattern replica of the waveguide design pattern (step C2) is pressed against

10 a layer of UV-sensitive polymer which has been spin coated onto the surface of the core layer, subsequently the UV-sensitive polymer is exposed through the mask and the pattern is developed (step C3). Following the exposure and development of the waveguide pattern into the polymer layer, the polymer pattern is used as masking material for dry etching (e.g. RIE –

15 Reactive Ion Etching, ICP – Inductively Coupled Plasma) into the core layer (step C3). In step C2), alternatively, a second mask system can be sandwiched between the core layer and the UV-sensitive polymer layer, which is used to enhance selectivity and waveguide core profile. In an embodiment of the invention this second mask system may consist of

20 oxide/polymer or nitride/polymer such as discussed for oxide polymers by J. M. Moran and D. Maydan: "High resolution, steep profile resist patterns" J. Vac. Sci. Technol., Vol. 16, No 6, Nov./Dec. 1979 and for nitride polymers by H. Namatsu, Y. Ozaki, and K. Hirata, "high resolution trilevel resist", J. Vac. Sci. Technol., 21(2), July/aug. 1982. In this way the design waveguide

25 pattern is transferred into the core layer having predetermined cross-sectional properties as well as refractive index. In order to protect the thus defined waveguide core, and in order to enhance symmetry in the structure transverse to the direction of propagation, a layer of silica with optical properties as close to those of the buffer layer as the chosen fabrication

30 technology permits is deposited on top of the core structure (step D). The formation of the latter layer (e.g. termed the upper cladding layer) may be formed using successive deposition and annealing steps (i.e. successive repetitions of steps D and E). It may be advantageous to ensure that the upper cladding layer has a lower flow temperature than that of the core and

35 lower cladding layers. This may be controlled by proper addition of boron,

phosphorus and/or fluorine (or any other dopants that reduces the flow temperature to the upper cladding layer).

A sample with a refractive index contrast of  $\Delta n/\langle n \rangle = 2.5\%$  was made  
5 according to the above mentioned procedure on top of 12 micron thermal  
oxide ( $\text{SiO}_2$ ). Spiral waveguides with a cross section of 3x3 micron<sup>2</sup> was  
fabricated and subsequently cladded with an optimized cladding procedure  
(a standard BPSG-cladding). The hereby obtained waveguides were  
characterized (as described in B. H. Larsen, et al., We1.2.6, ECOC-IOOC,  
10 2003) by direct, and hence, reliable propagation losses after propagation  
through up to 1 meter of waveguides. These characterization experiments  
reveal that when applying the parameters listed in EXAMPLE 1, it is possible  
to remove the overtone of the N-H absorption peak located at 1508 nm as  
indicated by the curve 'new process' in FIG. 4 illustrating optical absorption  
15 loss in dB/cm from  $\lambda=1500$  nm to  $\lambda=1600$  nm for a waveguide manufactured  
according to different processing conditions, respectively, 'with NH3', 'without  
NH3' and a 'new process' according to the invention.

By measuring the propagation loss as a function of the length at 1550 nm we  
20 have managed to fabricate waveguides with an extremely low loss below  
0.03 dB/cm over a very broad range of wavelengths, as seen in FIG. 5  
showing optical propagation loss in dB at  $\lambda=1550$  nm for a waveguide  
according to the invention as a function of waveguide length (in cm) and  
mode (TE or TM).

25 The sample made by the parameters listed under EXAMPLE 1 has been  
analyzed by Secondary Ion Mass Spectrometry (SIMS). Briefly the sample  
under investigation is sputtered by a flux of accelerated ions (here  $\text{Cs}^+$ ) by  
which material is continuously being removed from the surface layer. A  
30 simple monitoring and on-line analysis of fragments produced by sputtering  
will allow for chemical analysis as a function of sputtering time. By calibration  
of sputtering yield and by comparison with relevant references, the intensity  
of relevant fragments can directly be converted into concentrations (here e.g.  
N and P are relevant).

For the sample made by the procedure described in EXAMPLE 1 the N and P concentrations were determined to  $[N]=1.30 \cdot 10^{21}$  atoms/cm<sup>3</sup> and  $[P]=4.58 \cdot 10^{20}$  atoms/cm<sup>3</sup> corresponding to an  $[N]/[P]$  ratio of 2.83.

- 5 Assuming a density close to 2.3 g/cm<sup>3</sup> as has been reported for SiON-type materials (cf. "Plasma-enhanced growth, composition and refractive index of silicon oxy-nitride films", K. E. Mattsson, J. Appl. Phys. 77, No. 12, p.6616-6623, 1995) and a molar weight close to that of SiO<sub>2</sub> (28.086 g/mole + 2•15.999 g/mole = 60.0840 g/mole) one can convert the measured atomic densities to stoichiometric values since the density of a SiON type material is close to 2.3 g/cm<sup>3</sup> / 60.0840 g/mole = 0.0383 mole/cm<sup>3</sup>. Multiplying with Avogadro's constant  $N_a$  one obtain an atom density of  $2.3052 \cdot 10^{22}$  atoms/cm<sup>3</sup>.
- 10
- 15 This leads to the following relative concentrations y and z of nitrogen and phosphorus, respectively:

$$N_y: y = 1.30 \cdot 10^{21} / 2.3052 \cdot 10^{22} = 0.056$$

$$P_z: z = 4.58 \cdot 10^{20} / 2.3052 \cdot 10^{22} = 0.020$$

20

#### EXAMPLE 2

A sample comprising an optical waveguide according to the invention was made as described in example 1 with the only difference that the 5%PH<sub>3</sub>/95%N<sub>2</sub> gas flow was increased from 10 to 50 sccm. The hereby grown PECVD films delaminated upon annealing due to the high P-content.

25 Thus, there is an upper limited to the amount of PH<sub>3</sub> which can be present under PECVD growth of a core under the above mentioned process parameters.

30 BASIC ELEMENTS

For waveguides according to the invention comprising material of the composition Si<sub>a</sub>O<sub>x</sub>N<sub>y</sub>X<sub>z</sub>H<sub>v</sub>, the individual elements may be introduced – mainly from a vapour phase – from the following compounds:

35

**Silicon, Si:**

$\text{SiH}_4$ ,  $\text{SiF}_4$ ,  $\text{SiCl}_4$ ,  $\text{SiF}_4$ ,  $\text{Si}_2\text{H}_6$ ,  $\text{SiH}_2\text{Cl}_2$ ,  $\text{SiCl}_2\text{F}_2$ ,  $\text{SiH}_2\text{F}_2$  or any other silicon containing gases or solids involving the use of hydrogen, chlorine, oxygen or even from solid compounds such as  $\text{SiO}_x$  or spin on type glasses as well as

- 5 sol-gel compounds containing Si.

**Oxygen, O:**

$\text{N}_2\text{O}$ , NO,  $\text{N}_2$ ,  $\text{NO}_2$ ,  $\text{O}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{H}_2\text{O}_2$ , CO,  $\text{CO}_2$

10 **Nitrogen, N:**

$\text{N}_2\text{O}$ , NO,  $\text{N}_2$ ,  $\text{NO}_2$ ,  $\text{NH}_3$ ,  $\text{N}_2$

**Boron, B:**

$\text{B}_2\text{H}_6$  or from solid compounds such as  $\text{B}_2\text{O}_3$

15

**Aluminum, Al:**

$\text{AlH}_3$  or liquid solved Organo-Al complexes

**Phosphorus, P:**

20  $\text{PH}_3$

**Sulfur, S:**

$\text{H}_2\text{S}$ , SO,  $\text{SO}_2$

25 **Germanium, Ge:**

$\text{GeH}_4$  or solid compounds such as  $\text{GeO}_2$

**Arsenic, As:**

AsH<sub>3</sub>

30

**Antimony, Sb:**

Sb dissolved in Organo compounds.

**Carrier gas selected from:**

35  $\text{N}_2$ , He, Ne, Ar, Kr, Xe

AN EXAMPLE BASED ON ATOMIC CONCENTRATIONS

In the following a correlation is established between relative stoichiometric concentrations (the a, x, y, z, v's in  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v$ ) and corresponding atomic densities for various mass densities of the resulting material. This is e.g. of use when a SIMS measurement is made to determine the atomic concentration of a given sample.

- The 'atomic' concentration (units  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v/\text{cm}^3$ ) in a given volume of a  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v$  type material is calculated as the mass density ( $\rho$  ( $\text{g}/\text{cm}^3$ )) divided by the mole mass  $M_{\text{tot}}$  ( $\text{g}/\text{mole}$ ) multiplied by Avogadro's number  $N_a$ . The total mole mass of  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v$  is given by a weighted sum of the mole masses of the constituting elements, i.e.  $M_{\text{tot}} = a \cdot M_{\text{Si}} + x \cdot M_{\text{O}} + y \cdot M_{\text{N}} + z \cdot M_{\text{X}} + v \cdot M_{\text{H}}$ .
- 15 The individual atom densities  $N_{\text{at}}$  ( $\text{atoms}/\text{cm}^3$ ) of each type of atom will then be given by:

$$N_{\text{at}}(\text{Si}) = a / (a+x+y+z+v) \cdot \text{total number of atoms} = a \cdot \rho \cdot N_a / [(a+x+y+z+v) \cdot M_{\text{tot}}]$$

$$N_{\text{at}}(\text{O}) = x / (a+x+y+z+v) \cdot \text{total number of atoms} = x \cdot \rho \cdot N_a / [(a+x+y+z+v) \cdot M_{\text{tot}}]$$

$$20 N_{\text{at}}(\text{N}) = y / (a+x+y+z+v) \cdot \text{total number of atoms} = y \cdot \rho \cdot N_a / [(a+x+y+z+v) \cdot M_{\text{tot}}]$$

$$N_{\text{at}}(\text{X}) = z / (a+x+y+z+v) \cdot \text{total number of atoms} = z \cdot \rho \cdot N_a / [(a+x+y+z+v) \cdot M_{\text{tot}}]$$

$$N_{\text{at}}(\text{H}) = v / (a+x+y+z+v) \cdot \text{total number of atoms} = v \cdot \rho \cdot N_a / [(a+x+y+z+v) \cdot M_{\text{tot}}]$$

- In an embodiment of the invention the above method can be illustrated by assuming a type of structure such as  $\text{Si}_{(1-z)}\text{O}_{(2-y)}\text{N}_y\text{P}_z$  wherein P is taken as an example from the group of elements denoted by X in the general formula ('X' = B, Al, P, S, Ge, As, Sb). In this example, P is assumed to substitute Si and N to substitute O. The addition of a small amount of H<sub>v</sub> (either intentionally or unintentionally) is not expected to have a major impact on either  $\rho$  or  $M_{\text{tot}}$  due to the small size and mass of hydrogen as well as the small concentration of H expected. However, the local presence of H might be important since the material should be valence neutral, i.e.  $(1-z) \cdot [\text{oxidation state of Si}] + (2-y) \cdot [\text{oxidation state of O}] + y \cdot [\text{oxidation state of N}] + z \cdot [\text{oxidation state of P}] + v \cdot [\text{oxidation state of H}] = 0$ .

35

The reported oxidation states are:

**H:**

+1 and -1 with +1 being the most obvious configuration in connection with covalent hydrides

5

**O:**

-2 and -1, with -2 being the most obvious state

**Si:**

10    +4, +6, -2, with +4 being the most stable configuration in connection with  $\text{SiO}_2$  like materials

**N:**

15    +3, -3, +4, +5, with the -3 state being the most stable configuration in the present content

**P:**

+3, +5, -3, with +5 being the most stable state.

20    Thus one can write:

$(1-z) \cdot (+4) + (2-y) \cdot (-2) + y \cdot (-3) + z \cdot (+5) + v \cdot (+1) = 4 - 4z - 4 + 2y - 3y + 5z + v = z - y + v = 0$ ,  
 i.e.  $z = y - v$ , assuming the above mentioned oxidation states of the individual compounds. Thus in this simple model, a small amount of hydrogen will allow for  $z < y$ , i.e. for more nitrogen than phosphorus. Alternative valance states of  
 25    the constituents may not be neglected.

Assuming a  $\text{Si}_{(1-z)}\text{O}_{(2-y)}\text{N}_y\text{P}_z$  type of material,  $z$  will be between 0 and 1 and  $y$  will be between 0 and 2. In an embodiment of the invention,  $z$  will be between e.g. 0 and 0.2 and  $y$  will be between 0 and 0.1 and  $y > z$ . The  
 30    presence of hydrogen is not incorporated in the following calculations although a small amount may be present.

In the above mentioned intervals,  $M_{\text{tot}}$  has been calculated as:

$$M_{\text{tot}} = (1-z) \cdot M_{\text{Si}} + (2-y) \cdot M_{\text{O}} + y \cdot M_{\text{N}} + z \cdot M_{\text{P}}, \text{ with}$$

35     $M_{\text{Si}} = 28.086 \text{ g/mole}$

$M_{\text{O}} = 15.999 \text{ g/mole}$

$$M_p = 30.974 \text{ g/mole}$$

$$M_N = 14.007 \text{ g/mole}$$

The result for  $M_{\text{tot}}$  has been summarized in table 1. As can be seen from  
 5 table 1,  $M_{\text{tot}}$  is only varying between 59.69 g/mole and 60.17 g/mole.

z	y	mole mass (g/mole)																			
		0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19
0	60.08	60.08	60.04	60.02	60.00	59.98	59.98	59.94	59.92	59.90	59.88	59.88	59.84	59.83	59.81	59.79	59.77	59.75	59.73	59.71	59.69
0.01		60.09	60.07	60.05	60.03	60.01	58.89	59.87	59.85	59.83	59.91	59.89	59.87	59.85	59.83	59.81	59.79	59.77	59.75	59.73	59.71
0.02			60.10	60.08	60.06	60.04	60.02	60.00	59.98	59.98	59.94	59.92	59.90	59.88	59.86	59.84	59.82	59.80	59.78	59.76	59.74
0.03				60.11	60.09	60.07	60.05	60.03	60.01	59.89	59.87	59.95	59.93	59.91	59.89	59.87	59.85	59.83	59.81	59.79	59.77
0.04					60.12	60.10	60.08	60.05	60.04	60.02	60.00	59.98	59.96	59.94	59.92	59.90	59.88	59.86	59.84	59.82	59.80
0.05						60.13	60.11	60.09	60.07	60.05	60.03	60.01	59.99	59.97	59.95	59.93	59.91	59.89	59.87	59.85	59.83
0.06							60.14	60.12	60.10	60.08	60.06	60.04	60.02	60.00	59.98	59.96	59.94	59.92	59.90	59.88	59.86
0.07								60.15	60.13	60.11	60.09	60.07	60.05	60.03	60.01	59.99	59.97	59.95	59.93	59.91	59.89
0.08									60.16	60.14	60.12	60.10	60.08	60.06	60.04	60.02	60.00	59.98	59.96	59.94	59.92
0.09										60.16	60.14	60.12	60.10	60.08	60.07	60.05	60.03	60.01	59.99	59.97	59.95
0.1											60.17	60.15	60.13	60.11	60.09	60.07	60.05	60.03	60.01	59.99	59.97

Table 1: Mole mass (g/mole) for a  $\text{Si}_{(1-z)}\text{O}_{(2-y)}\text{N}_y\text{P}_z$  type material with  $z \in [0, 0.1]$ ,  $y \in [0, 0.2]$  and  $y > z$ .

Applying the above mentioned intervals, it is possible to calculate the atomic densities of Si, O, P and N when knowing the mass density ( $\rho$  (g/cm<sup>3</sup>)) of the material. However, the mass density is expected to vary with the atomic structure. For a PECVD SiON-type material, a density between 2.26 g/cm<sup>3</sup>  
 15 and 2.35 g/mole has been measured (cf. Kent Erik Mattsson, Ph.D thesis MIC, The Technical University of Denmark, 1994). For various forms of quarts, densities such as 2.32, 2.19, 2.26, 2.635, 2.13 g/mole can be found in "Handbook of chemistry and Physics" 66<sup>TH</sup> edition.

20 As an illustrative example, the mass density is assumed to be 2.3 g/mole for a  $\text{Si}_{(1-z)}\text{O}_{(2-y)}\text{N}_y\text{P}_z$  type material with  $z \in [0, 0.1]$ ,  $y \in [0, 0.2]$  and  $y > z$ . The corresponding atomic densities for Si, O, P, and N can be calculated. The resulting values are shown in tables 2, 3, 4, and 5, respectively, wherein  $10^{21}$   
 25 is written as 1E21, i.e. e.g.  $7.7 \cdot 10^{21}$  is written as 7.7E21.

		Y																				
		z	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.2
0		7.7E21																				
0.01		7.6E21																				
0.02		7.5E21																				
0.03		7.5E21																				
0.04		7.4E21																				
0.05		7.3E21																				
0.06		7.2E21																				
0.07		7.1E21																				
0.08		7.0E21																				
0.09		6.9E21																				
0.1																						

Table 2: Atomic density of Si (atoms/cm<sup>3</sup>) for a Si<sub>(1-z)</sub>O<sub>(2-y)</sub>N<sub>y</sub>P<sub>z</sub> type material with z ∈ [0, 0.1], y ∈ [0, 0.2] and y>z. The mass density is assumed to be 2.3 g/mole.

5

From table 2, it is seen that the density of Si is between 6.9E21 and 7.7E21 atoms/cm<sup>3</sup>, assuming ρ = 2.3 g/cm<sup>3</sup>.

10

		y																					
		z	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.2
0	0E+00	7.7E19	1.5E20	2.3E20	3.1E20	3.8E20	4.6E20	5.4E20	6.2E20	6.9E20	7.7E20	8.5E20	9.3E20	1.0E21	1.1E21	1.2E21	1.2E21	1.3E21	1.4E21	1.5E21	1.5E21		
0.01		7.7E19	1.5E20	2.3E20	3.1E20	3.8E20	4.6E20	5.4E20	6.2E20	6.9E20	7.7E20	8.5E20	9.3E20	1.0E21	1.1E21	1.2E21	1.2E21	1.3E21	1.4E21	1.5E21	1.5E21		
0.02		1.5E20	2.3E20	3.1E20	3.8E20	4.6E20	5.4E20	6.2E20	6.9E20	7.7E20	8.5E20	9.3E20	1.0E21	1.1E21	1.2E21	1.2E21	1.3E21	1.4E21	1.5E21	1.5E21	1.5E21		
0.03		2.3E20	3.1E20	3.8E20	4.6E20	5.4E20	6.2E20	6.9E20	7.7E20	8.5E20	9.3E20	1.0E21	1.1E21	1.2E21	1.2E21	1.3E21	1.4E21	1.5E21	1.5E21	1.5E21	1.5E21		
0.04		3.1E20	3.8E20	4.6E20	5.4E20	6.2E20	6.9E20	7.7E20	8.5E20	9.3E20	1.0E21	1.1E21	1.2E21	1.2E21	1.3E21	1.4E21	1.5E21	1.5E21	1.5E21	1.5E21	1.5E21		
0.05		3.8E20	4.6E20	5.4E20	6.2E20	6.9E20	7.7E20	8.5E20	9.3E20	1.0E21	1.1E21	1.2E21	1.2E21	1.3E21	1.4E21	1.5E21	1.5E21	1.5E21	1.5E21	1.5E21	1.5E21		
0.06		4.6E20	5.4E20	6.2E20	6.9E20	7.7E20	8.5E20	9.3E20	1.0E21	1.1E21	1.2E21	1.2E21	1.3E21	1.4E21	1.5E21								
0.07		5.4E20	6.1E20	6.8E20	7.7E20	8.5E20	9.2E20	1.0E21	1.1E21	1.2E21	1.2E21	1.3E21	1.4E21	1.5E21									
0.08		6.1E20	6.8E20	7.7E20	8.5E20	9.2E20	1.0E21	1.1E21	1.2E21	1.2E21	1.3E21	1.4E21	1.5E21										
0.09		6.8E20	7.7E20	8.4E20	9.2E20	1.0E21	1.1E21	1.2E21	1.2E21	1.3E21	1.4E21	1.5E21											
0.1		7.7E20	8.4E20	9.2E20	1.0E21	1.1E21	1.2E21	1.2E21	1.3E21	1.4E21	1.5E21												

Table 3. Atomic density of N (atoms/cm<sup>3</sup>) for a Si<sub>(1-z)</sub>O<sub>(2-y)</sub>N<sub>y</sub>P<sub>z</sub> type material with z ∈ [0, 0.1], y ∈ [0, 0.2] and y>z. The mass density is assumed to be 2.3 g/mole.

15

From table 3, it is seen that the density of N is between 0 and 1.5E21 atoms/cm<sup>3</sup>, assuming ρ = 2.3 g/cm<sup>3</sup>.

z	y																				
	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.2
0	0.0E00																				
0.01	7.7E19																				
0.02	1.5E20																				
0.03	2.3E20																				
0.04	3.1E20																				
0.05	3.8E20																				
0.06	4.6E20																				
0.07	5.4E20																				
0.08	6.1E20																				
0.09	6.9E20																				
0.1	7.7E20																				

Table 4. Atomic density of P (atoms/cm<sup>3</sup>) for a Si<sub>(1-z)</sub>O<sub>(2-y)</sub>N<sub>y</sub>P<sub>z</sub> type material with z ∈ [0, 0.1], y ∈ [0, 0.2] and y>z. The mass density is assumed to be 2.3 g/mole.

5

From table 4, it is seen that the density of P is between 0 and 7.7E20 atoms/cm<sup>3</sup>, assuming ρ = 2.3 g/cm<sup>3</sup>.

10

z	y																				
	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.2
0	1.5E22																				
0.01	1.5E22																				
0.02	1.5E22																				
0.03	1.5E22																				
0.04	1.5E22																				
0.05	1.5E22																				
0.06	1.5E22																				
0.07	1.5E22																				
0.08	1.5E22																				
0.09	1.5E22																				
0.1	1.5E22																				

Table 5. Atomic density of O (atoms/cm<sup>3</sup>) for a Si<sub>(1-z)</sub>O<sub>(2-y)</sub>N<sub>y</sub>P<sub>z</sub> type material with z ∈ [0, 0.1], y ∈ [0, 0.2] and y>z. The mass density is assumed to be 2.3 g/mole.

15

From table 5, it is seen that the density of O is between 1.4E22 and 1.5E22 atoms/cm<sup>3</sup>, assuming ρ = 2.3 g/cm<sup>3</sup>.

Similar evaluations can be performed for a range of mass densities around 2.3 g/mole. The hereby calculated maximal and minimal atomic densities have been summarized in table 6.

Masseyfylde g/cm <sup>3</sup>	Si atoms/ cm <sup>3</sup>		O atoms/ cm <sup>3</sup>		N atoms/ cm <sup>3</sup>		P atoms/ cm <sup>3</sup>	
	min	maks	min	maks	min	maks	min	maks
1.5	4.5E21	5.0E21	9.0E21	1.0E22	0.0E00	1.0E21	0.0E00	5.0E20
1.6	4.8E21	5.4E21	9.6E21	1.1E22	0.0E00	1.1E21	0.0E00	5.4E20
1.7	5.1E21	5.7E21	1.0E22	1.1E22	0.0E00	1.1E21	0.0E00	5.7E20
1.8	5.4E21	6.1E21	1.1E22	1.2E22	0.0E00	1.2E21	0.0E00	6.0E20
1.9	5.7E21	6.4E21	1.1E22	1.3E22	0.0E00	1.3E21	0.0E00	6.4E20
2	6.9E21	7.7E21	1.4E22	1.5E22	0.0E00	1.5E21	0.0E00	7.7E20
2.1	6.3E21	7.1E21	1.3E22	1.4E22	0.0E00	1.4E21	0.0E00	7.0E20
2.2	6.6E21	7.4E21	1.3E22	1.5E22	0.0E00	1.5E21	0.0E00	7.4E20
2.3	6.9E21	7.7E21	1.4E22	1.5E22	0.0E00	1.5E21	0.0E00	7.7E20
2.4	7.2E21	8.1E21	1.4E22	1.6E22	0.0E00	1.6E21	0.0E00	8.0E20
2.5	7.5E21	8.4E21	1.5E22	1.7E22	0.0E00	1.7E21	0.0E00	8.4E20
2.6	7.8E21	8.7E21	1.6E22	1.7E22	0.0E00	1.7E21	0.0E00	8.7E20
2.7	8.1E21	9.1E21	1.6E22	1.8E22	0.0E00	1.8E21	0.0E00	9.0E20
2.8	8.4E21	9.4E21	1.7E22	1.9E22	0.0E00	1.9E21	0.0E00	9.4E20
2.9	8.7E21	9.8E21	1.7E22	1.9E22	0.0E00	2.0E21	0.0E00	9.7E20
3	9.0E21	1.0E22	1.8E22	2.0E22	0.0E00	2.0E21	0.0E00	1.0E21
3.1	9.3E21	1.0E22	1.9E22	2.1E22	0.0E00	2.1E21	0.0E00	1.0E21
3.2	9.6E21	1.1E22	1.9E22	2.1E22	0.0E00	2.2E21	0.0E00	1.1E21
3.3	9.9E21	1.1E22	2.0E22	2.2E22	0.0E00	2.2E21	0.0E00	1.1E21
3.4	1.0E22	1.1E22	2.0E22	2.3E22	0.0E00	2.3E21	0.0E00	1.1E21
3.5	1.0E22	1.2E22	2.1E22	2.3E22	0.0E00	2.4E21	0.0E00	1.2E21
3.6	1.1E22	1.2E22	2.2E22	2.4E22	0.0E00	2.4E21	0.0E00	1.2E21
3.7	1.1E22	1.2E22	2.2E22	2.5E22	0.0E00	2.5E21	0.0E00	1.2E21
3.8	1.1E22	1.3E22	2.3E22	2.5E22	0.0E00	2.6E21	0.0E00	1.3E21
3.9	1.2E22	1.3E22	2.3E22	2.6E22	0.0E00	2.6E21	0.0E00	1.3E21
4	1.2E22	1.3E22	2.4E22	2.7E22	0.0E00	2.7E21	0.0E00	1.3E21

5

**Table 6.** Mass densities between 1.5 and 4 g/mole and the hereby maximum and minimum number of atoms per cm<sup>3</sup> assuming a Si<sub>(1-z)</sub>O<sub>(2-y)</sub>N<sub>y</sub>P<sub>z</sub> type material with z ∈ [0, 0.1], y ∈ [0, 0.2] and y>z.

- 10 Based on table 6 one can state that for a Si<sub>(1-z)</sub>O<sub>(2-y)</sub>N<sub>y</sub>P<sub>z</sub> type material with z ∈ [0, 0.1], y ∈ [0, 0.2] and y>z with a mass density between 1.5 and 4 g/cm<sup>3</sup> the atomic densities of Si, O, N and P will be in the ranges indicated below:

The atomic density of Si is between 4.5E21 and 1.3E22 atoms/cm<sup>3</sup>.

- 15 The atomic density of O is between 9.0E21 and 2.7E22 atoms/cm<sup>3</sup>.

The atomic density of N is between 0 and 2.7E21 atoms/cm<sup>3</sup>.

The atomic density of P is between 0 and 1.3E21 atoms/cm<sup>3</sup>.

In an embodiment of the invention (EXAMPLE 1), the density of N and P was  
5 determined to [N] = 1.30E21 atoms/cm<sup>3</sup> and [P] = 4.58E20 atoms/cm<sup>3</sup> which  
is within the above mentioned ranges for N and P.

FIG. 6 shows a schematic (x-y-plane) cross sectional view of an optical component 100 according to the invention comprising a base (or lower  
10 cladding) layer 61 formed on a substrate 10 with various waveguide core elements 31, 32, 33 applied to the base layer and covered by an upper cladding layer 62 (the combined cladding layers 61, 62 being denoted 6 in FIG. 6). The upper cladding layer has an upper surface 621, possibly being corrugated (although not to scale in FIG. 6) due to an anneal and reflow procedure. Waveguides 31, 32, 33 of different widths w<sub>1</sub>, w<sub>2</sub>, w<sub>3</sub>, respectively, and identical height h (equal to the thickness of the core layer) are shown.  
15 The waveguides have end facets 331 (assuming that the cross section of FIG. 6 is an 'end view' of a component). The substrate (e.g. a silicon substrate) 10 has a bottom essentially planar face 11 (x-z-plane).

20 The invention is defined by the features of the independent claim(s). Preferred embodiments are defined in the dependent claims.

25 Some preferred embodiments have been shown in the foregoing, but it should be stressed that the invention is not limited to these, but may be embodied in other ways within the subject-matter defined in the following claims.

CLAIMS

1. An optical waveguide for guiding light in a predefined wavelength range, the optical waveguide comprising core and cladding regions for confining light, the core and/or cladding region or regions being formed on a substrate, and the whole or a part of the core and/or cladding region or regions comprising material of the stoichiometric composition  $Si_aO_xN_yX_zH_v$ ,  
wherein  
X is selected from the group of elements B, Al, P, S, Ge, As, Sb and combinations thereof, and the ratio y/z is larger than 1, such as larger than 1.2, such as larger than 1.5, such as larger than 1.8, such as larger than 2.0, such as larger than 2.5, such as larger than 3.0, such as larger than 3.5, such as larger than 4.0, such as larger than 4.5, such as larger than 5.0, such as larger than 5.5, such as larger than 6.0, such as larger than 7.0,  
such as larger than 8.0.
2. An optical waveguide according to claim 1 wherein the ratio y/z is in the range from 1.0 to 100, such as 1.0 to 20, such as 1.0 to 10, such as 1.5 to 8.0, such as 2.0 to 4.0, such as 2.5 to 3.5.
3. An optical waveguide according to claim 1 or 2 wherein the number a defining the relative concentration of the element Si is in the range from 0.1 to 3.5 such as in the range from 0.9 to 1.1 or in the range from 2.9 to 3.1.
4. An optical waveguide according to any one of claims 1-3 wherein the number x defining the relative concentration of the element O is in the range from 0 to 2.5 such as in the range from 1.9 to 2.1 or in the range from 0 to 0.1.
5. An optical waveguide according to any one of claims 1-4 wherein the number y defining the relative concentration of the element N is in the range from 0 to 4.5 such as in the range from 3.9 to 4.1 or in the range from 0 to 0.5, such as in the range from 0.02 to 0.3, such as in the range from 0.03 to 0.2, such as in the range from 0.04 to 0.10.

6. An optical waveguide according to any one of claims 1-5 wherein the number z defining the relative concentration of the element X selected from the group comprising B, Al, P, S, Ge, As, Sb and combinations thereof is in the range from 0 to 0.3 such as in the range from 0.005 to 0.2, such as in the  
5 range from 0.01 to 0.10.
7. An optical waveguide according to any one of claims 1-6 wherein a is in the range from 0.8 to 1.2 and x is in the range from 1.8 to 2.2 and y is in the range from 0.01 to 0.5 and z is in the range from 0.005 to 0.2.  
10
8. An optical waveguide according to any one of claims 1-6 wherein a is in the range from 2.8 to 3.2 and y is in the range from 3.8 to 4.2 and x is in the range from 0.01 to 0.5 and z is in the range from 0.005 to 0.2.
- 15 9. An optical waveguide according to claim 1 wherein the number a defining the relative concentration of the element Si is in the range from 0.9 to 1.1, the number x defining the relative concentration of the element O is in the range from 1.9 to 2.1, the number y defining the relative concentration of the element N is in the range from 0.015 to 0.12, and the number z defining  
20 the relative concentration of the element X is in the range from 0.005 to 0.04.
10. An optical waveguide according to any one of the preceding claims wherein the optical absorption peak at  $\lambda=1508$  nm due to Si:N-H bonds is smaller than 0.1 dB/cm, such as smaller than 0.05 dB/cm such as smaller  
25 than 0.01 dB/cm.
11. An optical waveguide according to any one of the preceding claims wherein the number v defining the relative concentration of the element H is such that the relative concentration  $v/(a+x+y+z+v)$  of H in  $Si_aO_xN_yX_zH_v$  is smaller than  $10^{-2}$ , such as smaller than  $10^{-3}$ , such as smaller than  $10^{-4}$ , such  
30 as smaller than  $10^{-5}$ .
12. An optical waveguide according to any one of the preceding claims wherein the atomic concentration of hydrogen is larger than the atomic  
35 concentration of nitrogen and/or phosphorus.

13. An optical waveguide according to any one of the preceding claims wherein the atomic concentration of hydrogen is larger than 5 at.%.
14. An optical waveguide according to any one of the preceding claims 5 wherein the number v defining the relative concentration of the element H is such that the concentration v/y of H relative to N is smaller than  $10^{-2}$ , such as smaller than  $10^{-3}$ , such as smaller than  $10^{-4}$ .
15. An optical waveguide according to any one of the preceding claims 10 wherein the number v defining the relative concentration of the element H is such that the concentration v/z of H relative to X is smaller than  $10^{-2}$ , such as smaller than  $10^{-3}$ , such as smaller than  $10^{-4}$ , X being an element selected from the group comprising B, Al, P, S, Ge, As, Sb and combinations thereof.
16. An optical waveguide according to any one of the preceding claims 15 wherein the element or elements X or the material  $Si_aO_xN_yX_zH_v$  comprises at least 50% phosphorus such as at least 75% phosphorus such as at least 90% phosphorus, such as 100% phosphorus.
17. An optical waveguide according to any one of the preceding claims 20 wherein the element or elements X or the material  $Si_aO_xN_yX_zH_v$  comprises at least two elements X(1), X(2), ..., X(n) where  $n \leq 7$ , selected from the group comprising B, Al, P, S, Ge, As, Sb of relative concentration z<sub>1</sub>, z<sub>2</sub>, ..., z<sub>n</sub>, respectively, where  $z=z_1+z_2+z_3+\dots+z_n$  and wherein  $z_1/z$  is larger than 0.50 25 such as larger than 0.75 such as larger than 0.90.
18. An optical waveguide according to claim 17 wherein n=2 and X(1) is P and X(2) is B or Ge.
19. An optical waveguide according to claim 17 wherein n=3 and X(1) is P, X(2) is B and X(3) is Ge. 30
20. An optical waveguide according to any one of the preceding claims wherein the waveguide core and/or cladding layers comprise material of the 35 stoichiometric composition  $Si_{(1-z)}O_{(2-y)}N_yX_z$  wherein X is an element form the group comprising B, Al, P, S, Ge, As, Sb or a combination thereof.

21. An optical waveguide according to claim 20 wherein X is P.
22. An optical waveguide according to claim 20 or 21 wherein  $0 < y \leq 0.2$   
5 and  $0 < z \leq 0.1$ .
23. An optical waveguide according to any of the preceding claims wherein  
the atomic density of silicon  $N_{at}(Si)$  is in the range  $4.5 \cdot 10^{21} < N_{at}(Si) <$   
 $1.3 \cdot 10^{22}$ , such as in the range  $5.1 \cdot 10^{21} < N_{at}(Si) < 9.1 \cdot 10^{21}$ , the atomic density  
10 of oxygen  $N_{at}(O)$  is in the range  $9.0 \cdot 10^{21} < N_{at}(O) < 2.7 \cdot 10^{22}$ , such as in the  
range  $1.0 \cdot 10^{22} < N_{at}(O) < 1.8 \cdot 10^{22}$ , the atomic density of nitrogen  $N_{at}(N)$  is in  
the range  $0 < N_{at}(N) < 2.7 \cdot 10^{21}$ , such as in the range  $0 < N_{at}(N) < 1.8 \cdot 10^{21}$ ,  
and the atomic density of phosphorus  $N_{at}(P)$  is in the range  $0 < N_{at}(P) <$   
 $1.3 \cdot 10^{21}$ , such as in the range  $0 < N_{at}(P) < 9.0 \cdot 10^{20}$ .  
15
24. An optical waveguide according to any one of the preceding claims  
wherein the core and/or cladding region comprises material having a  
refractive index at a wavelength of 1550 nm in the range 1.45 – 2.02, such  
as in the range from 1.45 to 1.60, such as in the range from 1.48 to 1.56.  
20
25. An optical waveguide according to any one of the preceding claims  
wherein the optical waveguide is adapted to guide light in a wavelength  
range from 250 nm to 3.6 μm, such as in the range from 850 nm to 1800 nm.
26. An optical waveguide according to any one of the preceding claims  
wherein the optical waveguide is adapted to guide light comprising  
wavelengths in the range from 1260 nm to 1660 nm, such as in the range  
1530-1565 nm, or in the range 1460-1530 nm, or in the range 1360-1460  
nm, or in the range 1260-1360 nm.  
30
27. An optical waveguide according to any one of the preceding claims  
wherein the waveguide core and/or cladding further comprises a rare earth  
elements selected from the group of elements comprising Ce, Pr, Nd, Pm,  
Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu or combinations thereof.  
35

28. An optical waveguide according to any one of the preceding claims wherein one or more of the rare earth elements are present in molar concentrations in the range from 50 to 5000 ppm mole/mole.
- 5    29. An optical waveguide according to any one of the preceding claims wherein the core and/or cladding region further comprises one or more TE-dopant elements for controlling the thermal expansion of the waveguide.
- 10    30. An optical waveguide according to any one of the preceding claims the thermal expansion of one or more of the layers constituting the core and cladding regions of the waveguide is/are adapted to the thermal expansion of the substrate by adding one or more TE-dopant elements to said one or more layers of the waveguide.
- 15    31. An optical waveguide according to claim 29 or 30 wherein said TE-dopant element or elements are selected from the group of elements comprising Al, F, Ti, or combinations thereof.
- 20    32. An optical waveguide according to any one of claims 29-31 wherein said TE-dopant element or elements are present in the core/and or cladding region or regions in molar concentrations in the range from 0 to 5%.
- 25    33. An optical waveguide according to any one of claims 29-32 wherein said dopant element or elements are present in the core/and or cladding region or regions in amounts sufficient to provide a coefficient of thermal expansion between  $1 \times 10^{-7} \text{ }^{\circ}\text{C}^{-1}$  and  $15 \times 10^{-7} \text{ }^{\circ}\text{C}^{-1}$ .
- 30    34. A method of manufacturing an optical waveguide for guiding light in a predefined wavelength range, the optical waveguide comprising core and cladding regions for confining light,  
the method comprising the steps of  
A) providing a substrate,  
B) forming a lower cladding layer on the substrate,  
C) forming a core region of said optical waveguide on the lower cladding
- 35    layer,

- D) forming an upper cladding layer to cover the core region and the lower cladding layer;  
wherein the whole or a part of said waveguide core and/or cladding region or regions comprise material of the stoichiometric composition  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}_v$ , and
- 5    X is selected from the group of elements B, Al, P, S, Ge, As, Sb and combinations thereof, and wherein  $y>z$ , such as larger than 1.2, such as larger than 1.5, such as larger than 1.8, such as larger than 2.0, such as larger than 2.5, such as larger than 3.0, such as larger than 3.5, such as larger than 4.0, such as larger than 4.5, such as larger than 5.0, such as  
10    larger than 5.5, such as larger than 6.0, such as larger than 7.0, such as larger than 8.0.
35. A method according to claim 34 wherein step C) comprises the sub-steps
- 15    C1) forming a core layer on the lower cladding layer,  
C2) providing a core mask comprising a core region pattern corresponding to the layout of the core region of said optical waveguide, and  
C3) forming core regions using the core mask, a photolithographic and an etching process.
- 20    36. A method according to claim 34 or 35 wherein the substrate is a silicon or quartz substrate.
37. A method according to any one of claims 34-36 wherein the formation  
25    of layers on the substrate is made by plasma enhanced chemical vapour deposition.
38. A method according to claim 37 wherein a standard cluster tool CVD process chamber type PECVD-apparatus from Surface Technology Systems  
30    is used for the formation of layers on the substrate.
39. A method according to claim 37 or 38 wherein processing parameters of the PECVD-process are optimized with a view to minimizing the optical absorption around  $\lambda=1508 \text{ nm}$ .

40. A method according to any one of claims 37-39 wherein processing parameters to be optimized include one or more of the following:
- a) SiH<sub>4</sub> flow;
  - b) the N<sub>2</sub>O flow;
  - 5 c) the N<sub>2</sub> flow;
  - d) the NH<sub>3</sub> flow;
  - e) the power;
  - f) the pressure;
  - 10 g) the temperature;
  - h) the frequency;
  - i) the flow or flows comprising the element or elements X;
41. A method according to any one of claims 37-40 wherein
- a) the SiH<sub>4</sub> flow rate is in the range from 0 to 30 sccm, such as 10 to 30  
15 sccm;
  - b) the N<sub>2</sub>O flow rate is in the range from 0 to 1000 sccm, such as 100 to 400 sccm;
  - c) the N<sub>2</sub> flow rate is in the range from 0 to 3000 sccm, such as 1000 to 3000 sccm.
  - 20 d) the NH<sub>3</sub> flow rate is in the range from 0 to 300 sccm, such as 150 to 250 sccm;
  - e) the power is in the range from 0 to 1000 W, such as 400 to 1000 W.
  - f) the pressure is in the range from 100 to 500 mTorr, such as 200 to 500  
mTorr.
  - 25 g) the temperature is in the range from 200 to 500 °C, such as 200 to 400 °C.
  - h) the frequency is around 380 kHz or around 13.8 MHz.
42. A method according to claim 40 or 41 wherein the X=P and in i) the PH<sub>3</sub>  
30 flow is provided by PH<sub>3</sub> diluted in N<sub>2</sub> or another carrier gas.
43. A method according to claim 42 wherein in i) the PH<sub>3</sub> flow is provided  
by 5% PH<sub>3</sub> in N<sub>2</sub> with a flow rate of 0 to 50 sccm such as 2 to 20 sccm.
- 35 44. A method according to any one of claims 37-43 wherein processing parameters of the PECVD process essentially have the following values:

- a) SiH<sub>4</sub> flow rate 20 sccm;
  - b) the N<sub>2</sub>O flow rate 100-400 sccm;
  - c) the N<sub>2</sub> flow rate 2000 sccm;
  - d) the NH<sub>3</sub> flow rate is 100 sccm;
- 5      e) the power is 700 W;
- f) the pressure is 250 mTorr;
  - g) the temperature 350 °C;
  - h) the frequency is 380 kHz;
  - i) 5%PH<sub>3</sub> in N<sub>2</sub> flow rate 10 sccm;
- 10     45. A method according to any one of claims 40-44 wherein in step i) the flow gas is selected among the group of gases SiH<sub>4</sub>, SiF<sub>4</sub>, SiCl<sub>4</sub>, SiF<sub>4</sub>, Si<sub>2</sub>H<sub>6</sub>, SiH<sub>2</sub>Cl<sub>2</sub>, SiCl<sub>2</sub>F<sub>2</sub>, SiH<sub>2</sub>F<sub>2</sub>, N<sub>2</sub>O, NO, N<sub>2</sub>, NO<sub>2</sub>, O<sub>2</sub>, H<sub>2</sub>O, H<sub>2</sub>O<sub>2</sub>, CO, CO<sub>2</sub>, N<sub>2</sub>O, NO, N<sub>2</sub>, NO<sub>2</sub>, NH<sub>3</sub>, N<sub>2</sub>, B<sub>2</sub>H<sub>6</sub>, AlH<sub>3</sub>, PH<sub>3</sub>, H<sub>2</sub>S, SO, SO<sub>2</sub>, GeH<sub>4</sub>, AsH<sub>3</sub>, or combinations thereof.
- 15     46. An optical waveguide obtainable by a method of manufacturing as defined in any one of claims 34-45.
- 20     47. An optical device comprising an optical waveguide as defined in any one of claims 1-33 or 46.
- 25     48. An optical device according to claim 47 comprising a branching component, such as a splitter or an arrayed waveguide grating.

**A LOW LOSS OPTICAL WAVEGUIDE, A METHOD OF ITS  
MANUFACTURE AND AN OPTICAL DEVICE**

**ABSTRACT**

The invention relates to an optical waveguide for guiding light in a predefined wavelength range, the optical waveguide comprising core and cladding regions for confining light, the core and/or cladding region or regions being formed on a substrate and comprising material of the stoichiometric composition  $\text{Si}_a\text{O}_x\text{N}_y\text{X}_z\text{H}$ . The invention further relates to a method of manufacturing an optical waveguide, an optical waveguide obtainable by the method and an optical device comprising such a waveguide. The object of the present invention is to provide an optical waveguide with low optical loss due to a reduced hydrogen bond-originated absorption. The problem is solved in that X is selected from the group of elements B, Al, P, S, Ge, As, Sb and combinations thereof, and the ratio y/z is larger than 1. This has the advantage that a low optical absorption in the waveguide may be achieved, possibly over a broad wavelength range. Further, a relatively low annealing temperature may be used yielding a relatively low induced strain whereby a low birefringence may be achieved. The optical waveguide may e.g. be manufactured by PECVD, which is ideal for the further processing of low loss waveguides. Waveguides according to the invention show superior transmission characterized with losses below 0.05 dB/cm between 900 nm and 1600 nm. In particular the absorption due to the second overtone of the Si:N-H vibration may be lowered to a value below the detection level. The invention may e.g. be used for the optical communications systems, in particular for branching components (e.g. splitters) and components for wavelength division multiplexing (WDM) systems, e.g. telecommunication systems.

(FIG. 4 should be published)

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Modtaget

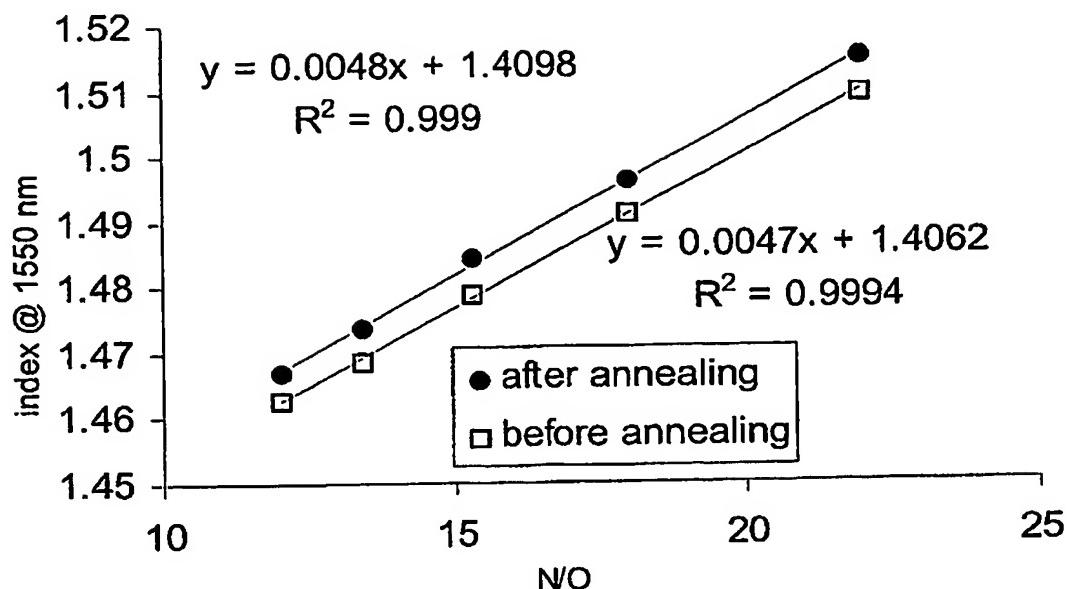


FIG. 1

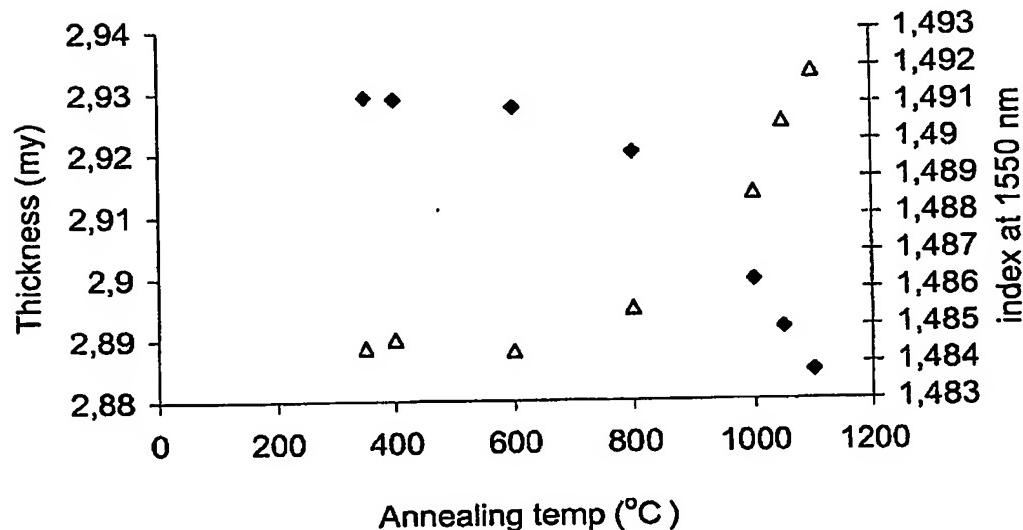


FIG. 2

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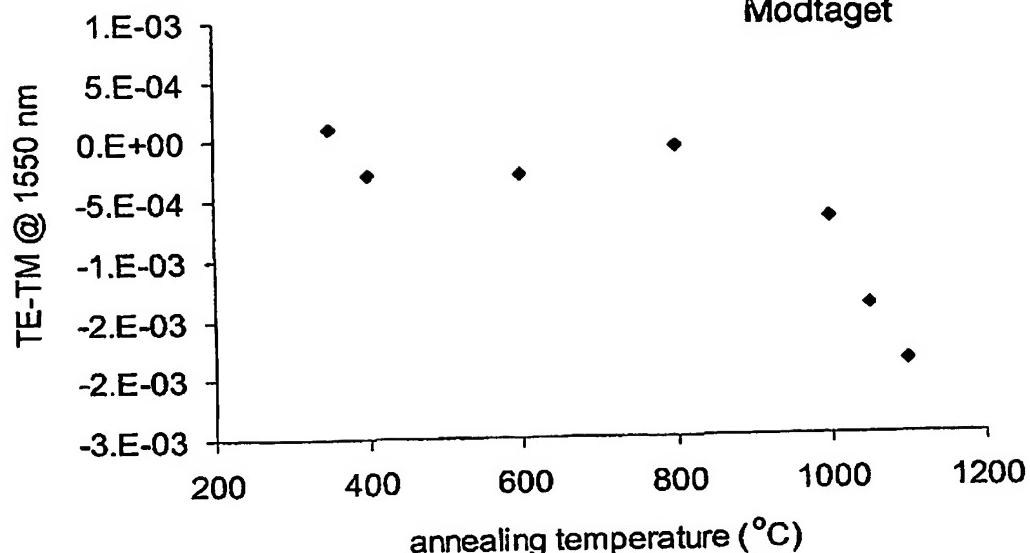


FIG. 3

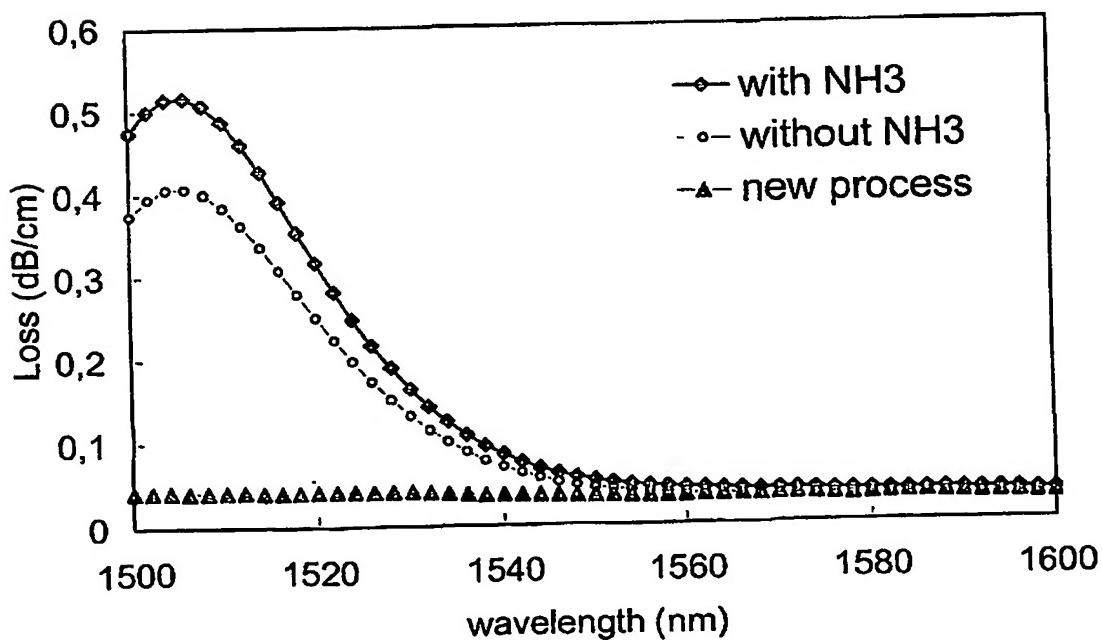


FIG. 4

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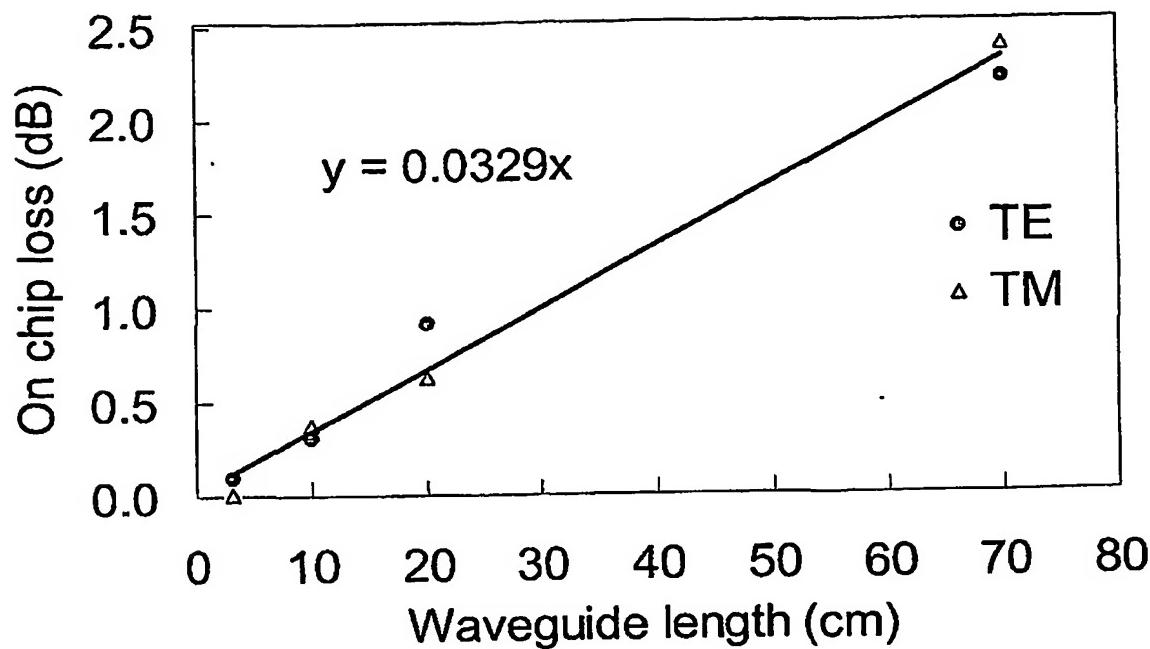


FIG. 5

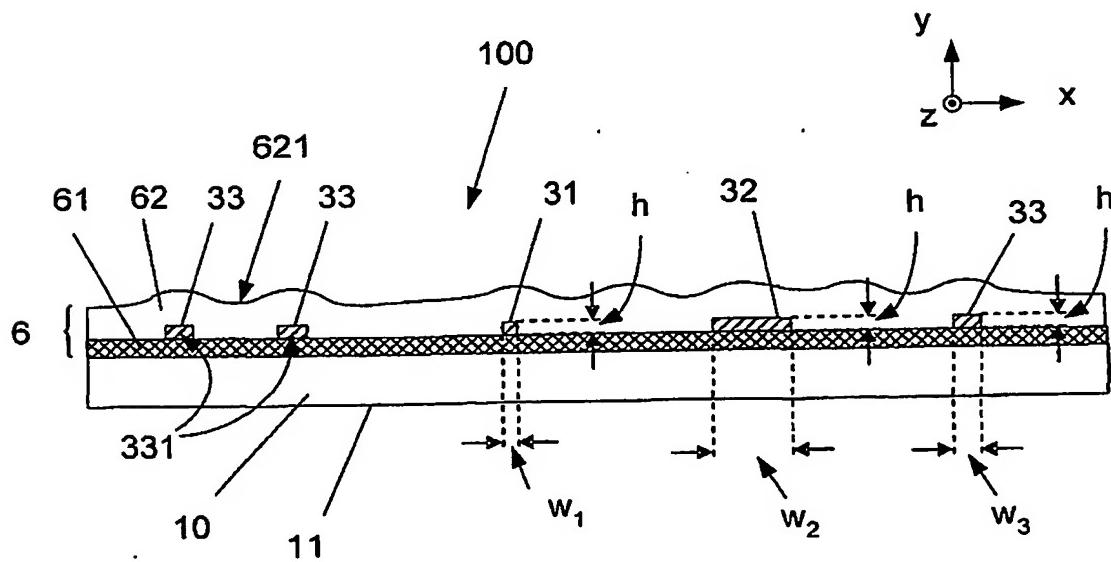


FIG. 6

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